

Coping with the Dunkelflaute: Power system implications of variable renewable energy droughts in Europe

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Abstract

Coping with prolonged periods of low availability of wind and solar power, also referred to as “Dunkelflaute”, emerges as a key challenge for realizing a decarbonized European energy system fully based on renewable energy sources. Here we investigate the role of long-duration electricity storage and geographical balancing in dealing with such variable renewable energy droughts. To this end, we combine renewable availability time series analysis and power sector modeling, using 36 historical weather years. We find that extreme drought events define long-duration storage operation and investment. The most extreme event in Europe occurred in the winter of 1996/97. Assuming policy-relevant interconnection, long-duration storage of 351 TWh or 7% of yearly electricity demand is required to deal with this event. As it affects many countries simultaneously, a storage capacity of 159 TWh or 3% of yearly electricity demand remains required even in the extreme case of unconstrained geographical balancing. Before and during Dunkelflaute events, we find complex interactions of long-duration storage with other flexibility options. Sensitivity analyses illustrate that firm zero-emission generation technologies would only moderately reduce long-duration storage needs. Thus, policymakers and system planners should prepare for a rapid expansion of long-duration storage capacity to safeguard the renewable energy transition in Europe. We further argue that using multiple weather years that include pronounced renewable energy droughts is required for weather-resilient energy system modeling.

Keywords: variable renewable energy, variable renewable energy droughts, long-duration storage, power sector modeling

1. Introduction

To mitigate climate change and to meet international commitments, the European Union aims to achieve net zero emissions of greenhouse gases by 2050. The electricity sector will play a central role in a decarbonized economy. Massively expanding renewable energy sources would not only allow for rapid decarbonization of the power sector but also for substituting the use of fossil fuels in other sectors, such as

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industry, transport, and heat, via electrification, also referred to as “sector coupling” [1–5].

The potentials of firm renewable energy sources, such as hydroelectric or bioenergy, are limited in most European countries. In contrast, wind and solar power offer vast expansion potentials and promise declining costs [6, 7]. Therefore, variable wind and solar power will likely form the backbone of the transition to net zero in most European countries [1, 8].

With a rising share of variable renewable energy (VRE), the European power system becomes increasingly exposed to weather variability [9, 10]. This has spurred a debate in the energy policy domains about the security of supply [11–20]. Of particular concern are long-lasting periods also referred to as “VRE droughts” or the German term “Dunkelflaute”, which are characterized by a very low availability of renewable energy sources [21, 22].

Previous research has shown that growing shares of VRE require an increasing amount of flexibility in the power sector. This can be provided by different types of electricity storage, demand response, or cross-border transmission [23–27]. While a wide range of flexibility technologies can help to cope with VRE droughts, it is a central option as it can shift temporary surplus energy to periods of low wind and solar availability across long time scales [28–30]. Reconversion of hydrogen or hydrogen-based derivatives to electrical energy, which are produced with renewable electricity, appears as the most promising option for storing renewable energy over long periods [29, 31, 32].

Spatial flexibility, facilitated by the interconnection between different countries, allows balancing of regional variations in demand and variable renewable supply [33, 34]. In Europe, cross-border interconnection can mitigate energy storage needs, particularly by balancing differences in wind power availability across countries [35]. Yet, it is unclear to what extent this storage-mitigating effect of geographical balancing remains feasible in extreme pan-European VRE droughts of synoptic scale, which may affect many countries simultaneously [30].

In this paper, we analyze the impact of VRE droughts on long-duration storage operation and sizing in a fully renewable European electricity system. We further investigate how varying levels of geographical balancing via interconnection affect these long-duration storage needs. We also examine how different technologies interact during extreme VRE droughts.

While the research interest in VRE droughts and their electricity system implications is growing, respective analyses vary regarding the research subject and the temporal and spatial scope [22]. One strand of the literature focuses on VRE droughts characterization based on time series of wind speed, solar irradiation, or normalized renewable availability factors. This includes analyses of historic or future wind droughts for Germany [36], the North Sea [37], Ireland [38], or the UK [39–42]. These studies typically focus on frequency-duration distributions, return periods, or spatio-temporal correlations. Wind droughts have been studied as VRE anomalies, i.e., cumulative deviations from climatological means or other reference profiles, on a global scale [43] or for the Netherlands [44]. Combining wind and solar power in renewable technology portfolios can mitigate drought characteristics within regions. This portfolio effect has been

studied for Europe [21, 30, 45–48], the U.S. [49], or individual countries, such as Germany [50, 51], Hungary [52], India [53], and Japan [54]. In addition, the complementary of wind and solar power across regions further reduces extreme drought severity. This balancing effect has been shown for Europe [30, 47, 48, 50] and the U.S. [49].

Another literature strand explores positive residual load events, which relate to periods where VRE generation falls short of electrical demand [22]. These periods indicate the need for system flexibility, particularly for long-duration storage assuming limited potential for geographical balancing via transmission. Positive residual load events have been studied for Europe [21, 55–58], Norway, France, Italy, Spain and Sweden [59], Germany [60], Northern Italy [61], Africa [62], or the U.S. [63].

VRE droughts that cause electricity system stress events can be detected through extreme electricity prices, shadow prices reflecting the value of the stored energy or transmission grid capacity, resource adequacy metrics, or emission patterns, as shown for Europe [64] or the U.S. [65–68]. Abstracting from cross-border electricity exchange and using historic renewable availability, Ruhnau and Qvist [60] find 55 TWh long-duration electricity storage is required in a renewable German power system for dealing with the most extreme positive residual load event, which occurred in winter 1996/97. Another model-based study by Kondziella et al. [69] finds that 67 TWh hydrogen storage is needed to deal with a stylized 2-week Dunkelflaute in Germany, featuring low wind and solar generation and high electricity demand. The long-duration storage capacity required to cope with renewable energy droughts corresponds to around 10% [60] or 9% [69] of the assumed yearly electricity demand in these two studies on Germany.

Energy system models increasingly include multiple sectors and energy carriers to explore future scenarios of sector-coupled energy systems [70, 71]. Due to increasing complexity and computational burden, these models are often solved for only a single or a limited number of weather years. However, optimal energy model outcomes vary substantially across years. These variations include optimal dispatch and investment decisions for electricity generation based on fossil fuels or renewable sources, electricity storage, or transmission grid capacities, as well as electricity demand, prices, leveled costs of electricity, or emissions. This is well-documented for single countries such as the UK [9, 72–75] or Ireland [75], for overall Europe [10, 76–80], or the U.S. [29, 81, 82]. For Europe, [80] quantify the robustness of future net-zero energy system design to weather years and find that overall system costs vary between $\pm 10\%$ depending on the year used for system design. A general finding of this strand of the literature is that energy systems modeling based on only one or a few weather years identifies system configurations that may lead to suboptimal capacity choices or operational inadequacies. Extreme renewable drought events, which vary substantially across years and regions, are likely to contribute significantly to these inter-annual variations in energy system modeling [30].

While there is growing interest in the meteorology and energy systems analysis domains on the impact of weather variability on renewable energy systems [68, 83], the literature lacks a distinct analysis of the impact of extreme renewable drought events on energy storage needs, and how spatial system flexibility

alleviates these.

In this paper, we combine two open-source methods to investigate how VRE droughts impact the need for long-duration storage in a fully decarbonized European power sector, using renewable time series analysis and a capacity expansion model of the power sector. We further quantify how much long-duration storage can be avoided with different degrees of electricity and hydrogen exchange between countries. We determine the long-duration storage need for dealing with extreme renewable droughts considering policy-oriented European interconnection levels, what “no-regret” long-duration storage capacity remains for a scenario with unconstrained geographical balancing of such events, and how much these results vary across years. In doing so, we also shed light on appropriate weather year selection for modeling weather-resilient energy system scenarios in Europe and illustrate how different types of flexibility options interact while coping with extreme renewable droughts.

2. Methods

In this study, we combine two methods: a VRE drought analysis based on availability time series of wind and solar power, and a cost-minimizing capacity expansion model of the European power system.

2.1. Variable renewable energy droughts identification: method and data

We use the open-source tool Variable Renewable Energy Drought Analyzer (VREDA) to identify and evaluate VRE drought patterns based on availability time series. VREDA has been designed to implement good practices of multi-threshold drought identification as outlined by Kittel and Schill [22] and has been applied before to characterize drought patterns in Europe [30]. It employs the variable-duration Mean-Below-Threshold (VMBT) method for drought identification, which varies the permissible drought duration between two full calendar years and one hour. This method searches for periods where renewable availability has a moving average below a specific drought qualification threshold by iteratively decreasing the drought duration. In each iteration, the algorithm sets the averaging interval to the respective event duration. Initially, it searches for drought events that last two full years and iteratively decreases the averaging interval to identify shorter events. A time series section with a moving average below the drought threshold identifies a drought event. It is then excluded from subsequent iterations, in which the averaging interval decreases further and additional (shorter) events are identified.

The iterative procedure of VMBT overcomes shortcomings of previous research [22]. The method allows for pooling of adjacent periods that independently may not qualify as VRE drought to capture longer-lasting events, i.e., intermediate periods with a renewable availability above the drought threshold. It further identifies unique events, avoids double counting as well as overlaps with adjacent events, and captures the full temporal extent of drought periods (“event” definition). The code and input data of the drought analysis tool are publicly available on GitLab at https://gitlab.com/diw-evu/variable_renewable_energy_droughts_analyzer.

We use country-level VRE availability time series provided by the Pan-European Climate Database, including 36 weather years from 1982 to 2016 for on- and offshore wind and solar photovoltaics (PV) [84].

For comparability across regions, drought thresholds are determined as a fraction of country-specific long-run mean availability factors for the period 1982 to 2016 [22]. These fractions range from 10 to 100% of mean availability, reflecting different levels of drought severity, increasing in 5% increments. Periods that qualify as drought events based on lower thresholds are likely brief and severe with very low availability. In contrast, events identified by higher thresholds may last substantially longer, i.e., up to several weeks or months [30].

We analyze drought patterns for renewable technology portfolios, comprising on- and offshore wind power as well as solar PV, for two cases that differ regarding the assumed electricity transmission between countries [22]: completely isolated countries (“energy islands”) or perfect interconnection across all countries (pan-European “copperplate”). For the energy islands scenario, we combine all technology-specific time series into a portfolio time series using capacity-weighted averages. The respective weights are based on policy-relevant assumptions on renewable capacity mixes from the Ten Year Network Development Plan (TYNDP) 2022 (scenario “Distributed Energy”) [85]. We update these assumptions for Germany according to the latest government targets [86]. For the copperplate scenario, we combine all country-level portfolio time series into a single pan-European composite time series, using weights according to the TYNDP 2022 (scenario Distributed Energy).

We use the “drought mass” metric devised by Kittel and Schill [30] to identify extreme drought events by aggregating the drought patterns of numerous single-threshold analyses, ranging in 5%-increments from the 10% to 75% threshold. To compute the drought mass score, we first modify these patterns by assigning the value 1 to drought hours and the value 0 to those hours that do not qualify as drought for each threshold. Next, we equally weigh the resulting drought patterns across all thresholds. We then accumulate the hourly scores up to the cut-off threshold 75%, excluding the drought patterns based on higher thresholds. This approach determines the multi-threshold event duration according to the 75%-analysis, while the event drought mass aggregates the drought patterns identified by included thresholds. The highest cumulative score identifies the most extreme event per summer-to-summer planning horizon.

Wind droughts are more frequent and severe in summer than in winter [30, 36, 39]. In countries with high wind shares in their capacity portfolio, the most extreme renewable portfolio drought events may thus occur in summer. Since peak electricity demand periods usually occur in winter in Central and Northern European countries, summer droughts generally matter less than winter droughts. To account for this, we compute a yearly drought mass score for droughts occurring throughout the summer-to-summer planning horizon and a winter drought mass score for drought events between October and March. When illustrating the relation of drought patterns and long-duration storage operation, we display both the most extreme summer and winter droughts if the highest drought mass score relates to summer drought (compare gray and teal boxes in Figure 1). Conversely, we mark only one event if the highest yearly drought mass score

refers to a winter drought (compare gray boxes only in Figure 1).

2.2. Power sector model

We use the open-source dispatch and capacity expansion model of the European power sector Dispatch and Investment Evaluation Tool with Endogenous Renewables (DIETER) [24, 87, 88] to analyze the interaction between VRE droughts and long-duration storage needs in a fully renewable European power system. The model features a simple transport model for exchanging electricity across countries, abstracting from grid constraints within countries. It has previously been applied to study various aspects of VRE integration and their interaction with flexibility options or sector coupling technologies [35, 88–97]. DIETER is a linear program that determines least-cost capacity and dispatch decisions, optimizing over all contiguous hours of a full year under perfect foresight.

Exogenous model inputs entail techno-economic parameters such as investment and variable costs, availability time series of wind and solar PV, as well as price-inelastic demand time series for electricity and hydrogen. Model results can be interpreted as the outcomes of a perfect, frictionless European electricity market, where all power generators maximize their profits. Costs are minimized for the overall system, depending on interconnection assumptions. In the energy islands case, costs are optimized for every country in isolation.

While the general model formulation of DIETER has been described extensively in the papers mentioned above, we use a version that features an improved representation of hydrogen technologies in this study. The model includes the generation, storage, and transport of renewable hydrogen technologies as well as its re-conversion to electricity. The hydrogen-based long-duration storage energy capacity denotes the lower heating value of the storage working gas. A formal definition of the novel equations is available in the Supplementary information SI.1.

For transparency and reproducibility, we provide the model code, the input data, and a manual in public repositories under permissive licenses available on GitLab at <https://gitlab.com/diw-evu/projects/power-sector-droughts/>.

2.3. Scenarios

Our analysis comprises 33 European countries (EU27, the UK, Norway, Switzerland, and the Western Balkans). We analyze and compare the impact of VRE droughts on long-duration storage needs for four different interconnection scenarios: (1) all countries operate as energy islands without exchange of electricity or hydrogen between countries; (2) cross-border exchange of electricity in line with the assumptions on the European transmission grid in 2050 projected by the TYNDP 2022 [85] (scenario Distributed Energy), while hydrogen exchange remains disabled; (3) cross-border electricity and hydrogen exchange according to the TYNDP 2022 (scenario Distributed Energy); and (4) unlimited exchange of electricity and hydrogen, i.e., all countries are perfectly integrated as pan-European copperplate. Note that VRE drought analysis based on renewable availability time series can only be carried out for the two extreme interconnection settings energy islands and copperplate (compare Section 2.1).

These varying degrees of interconnection allow distinguishing several effects. First, scenario (1) identifies maximal long-duration storage needs across European countries, excluding geographical balancing of VRE droughts between countries [30]. Second, comparing scenarios (2) and (3) disentangles the effects of policy-oriented electricity and hydrogen interconnection levels on long-duration storage needs. Finally, the copperplate scenario (4) identifies minimal long-duration storage needs, including unconstrained geographical balancing of VRE droughts, which can be interpreted as unavoidable or “no-regret” investments in a fully renewable European energy system. We abstract from grid investment costs but impose losses on hydrogen exchange related to compression for long-distance transport via pipeline.

We investigate a large number of weather years that differ in renewable availabilities and demand patterns. These weather years range from 1982 to 2016. Extreme VRE droughts often occur in European winter, may last up to several weeks, and span across the turn of years [30]. Hence, we use a summer-to-summer planning horizon (in line with [60, 64], but unlike, e.g., [80]), comprising 8760 consecutive hours. Note that we independently optimize the capacity mix for every year.

2.4. Input data, technology portfolio, and capacity bounds

To quantify the maximum impact of VRE droughts on long-duration storage, we model fully renewable supply scenarios, excluding carbon capture and storage (CCS) and fossil fuel-based dispatchable generation technologies. This is not enforced by binding renewable or carbon emission targets [92], but rather by limiting the available generation technology portfolio to zero-emission options. These include solar PV, on- and offshore wind power, bioenergy, and different types of hydroelectric power (run-of-river, reservoir, pumped-hydro). In a sensitivity analysis, we add a generic firm zero-emission generation technology.

For policy relevance, we allow generation capacity expansion within lower and upper potentials of the TYNDP 2024 [98]. Additionally, we assume an annual generation limit for bioenergy in line with the TYNDP 2022 [18]. Installed power and energy capacities of the available hydro technologies are fixed to values provided in European Resource Adequacy Assessment (ERAA) 2021 [99].

We include underground hydrogen storage as a long-duration storage option. Underground cavern and porous storage energy potentials vary substantially across countries, including newly built and retrofitted storage facilities from natural gas infrastructure [100, 101]. We constrain the expansion of long-duration storage energy capacities accordingly. For simplicity, we abstract from any differentiation between underground storage types and aggregate their potentials for each modeled country.

In our analysis, we attempt to illustrate the impact of persistent VRE droughts lasting longer than a few days on the power sector, notably regarding long-duration electricity storage. We thus abstract from an explicit representation of sector coupling options as well as seasonal heat storage. To this end, we use near-term demand profiles, retrieved from ERAA 2021 [99] (representative for the year 2025). The profiles are scaled to the annual demand levels of the TYNDP (scenario Distributed Energy for 2050) and are reduced by the electrical energy amount required for the generation of the exogenous hydrogen demand.

We use the Pan-European Climate Database for renewable availability factors of on- and offshore wind and solar PV [84], as well as the hydro inflow, retrieved from the ERAA 2021 [99].

3. Results

3.1. Extreme renewable energy droughts coincide with major discharging periods of long-duration storage

To analyze the impact of VRE droughts on long-duration storage, we first provide an intuition on how the long-duration storage operation is affected by such events. Figure 1 illustrates drought patterns of the renewable technology portfolios and long-duration storage operation for the weather year 1996/97, which comprises the most extreme pan-European drought we find in the data (Figure SI.2), affecting many European countries simultaneously [30]. For each region, it shows the events with the highest drought mass score, which comprise sequences of shorter but more severe droughts within contiguous periods of well-below-average renewable availability that may last up to several months and span across the turn of years.

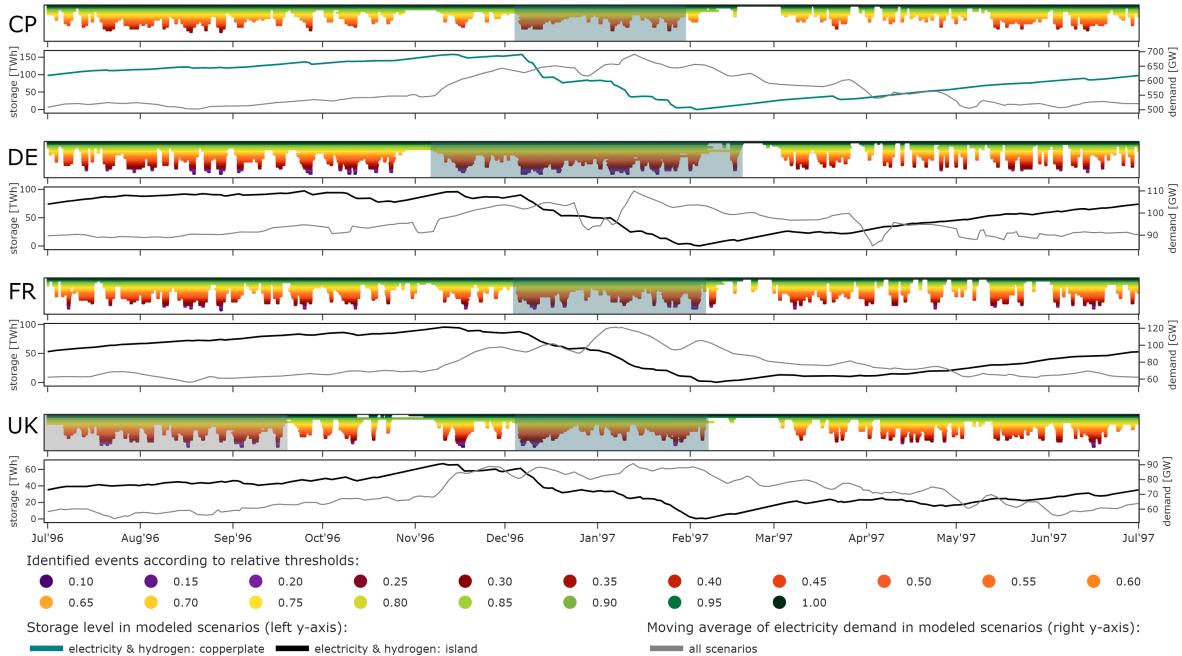


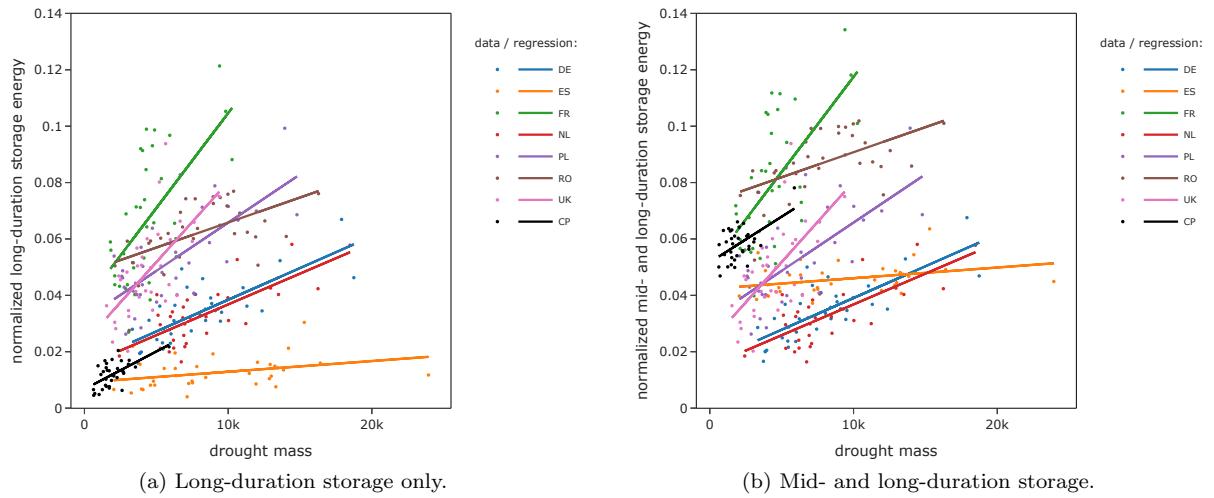
Figure 1: Drought events, electricity demand, and state-of-charge of long-duration storage in winter 1996/97.

During these long-lasting events, average renewable availability is well below its long-run mean, but still remains above zero. This means that long-duration storage is not necessarily required to continuously discharge during the entire identified drought event. However, these longer events comprise shorter periods with significantly lower availability, lasting multiple days or even two to three weeks. In these periods, storage is discharged at capacity and the storage state-of-charge accordingly declines, particularly when co-occurring with peak-demand periods.

Extreme events typically occur in winter, leading to significant long-duration discharge periods. Countries that heavily rely on wind power, such as the UK, may face the most extreme renewable technology portfolio events also in summer, driven by wind droughts that are generally more pronounced in summer in Europe [30, 36, 39]. Yet, the UK’s electricity demand is much higher in winter than in summer, similar to other central and northern European countries. As this seasonal demand effect by far outweighs the differences between summer and winter droughts, UK’s major storage discharging period still coincides with the winter drought. In contrast, the slightly larger summer drought hardly affects the storage state-of-charge.

3.2. Droughts drive long-duration storage energy capacity

The most severe drought events define not only major periods of long-duration storage discharge. For each modeled weather year, there is also a clear positive correlation between the most extreme renewable droughts in a given country and that country’s long-duration storage energy need (Figure 2a). We find that this applies to nearly all European countries modeled as energy islands and also to the pan-European copperplate scenario.



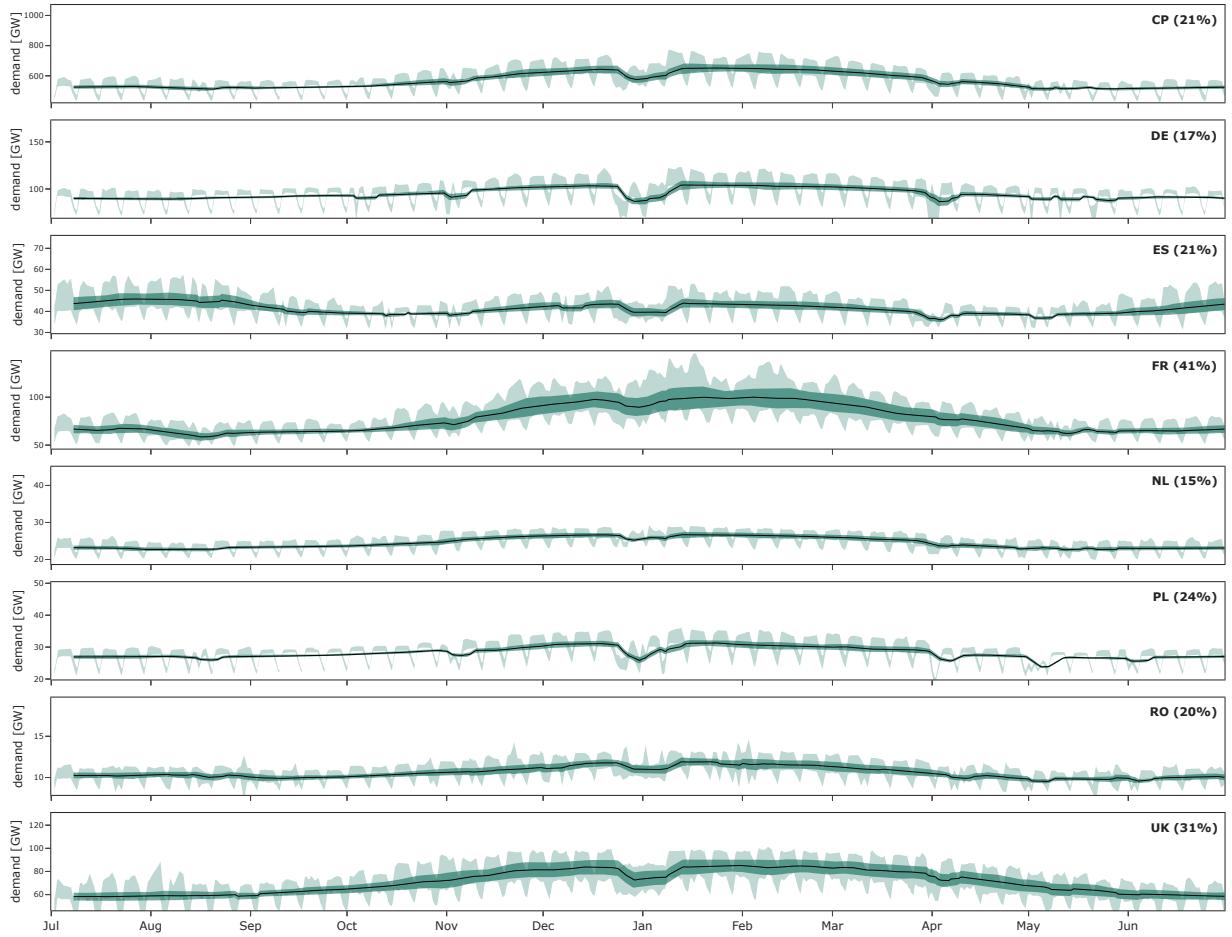
Notes: For comparison, we normalize the optimal storage energy with the annual demand for electricity (including electrified heating) and hydrogen. For illustration, we exclude countries with optimal storage energy below 5 TWh or investment at potential. Figure SI.3 shows the unfiltered regression results and emphasizes the substitutability of mid- and long-duration storage needs.

Figure 2: Correlation of the drought mass of most extreme winter drought events and normalized storage energy capacity.

The correlation between the most extreme winter drought events and storage needs differs between countries. In Central European countries such as France or the UK, storage capacity increases substantially in years with more severe droughts, illustrated by the steep gradient of the fitted regression lines in Figure 2. This is because electricity demand has a pronounced winter peak in these countries (Figure 3). In contrast, more severe droughts hardly increase storage needs in other countries, particularly in Romania or Spain, driven by a less seasonal or even summer-peaking electricity demand in such countries. A complementary Germany-only analysis using flat electricity demand profiles exemplarily disentangles the storage-defining effect of renewable droughts from the storage-driving effect of demand seasonality for the German power sector (compare blue and orange lines in Figure SI.4). The gradient of the regression line decreases when

flattening electricity demand profiles, i.e., the storage-defining effect of droughts is less pronounced.

There is also a combined level and gradient effect. Normalized long-duration storage energy needs are generally much lower in Spain or the pan-European Copperplate than those in Central or Northern European countries. One driving factor for this are significant hydro reservoir and pumped-hydro storage capacities in Spain or Europe, which substitute long-duration storage needs for dealing with extreme droughts to some extent. This leads to a lower sensitivity of long-duration storage needs to increasingly severe droughts, visible as lower regression line intercepts and, in the case of Spain, a low regression coefficient. Considering both hydro and long-duration storage capacities for the regression eliminates this effect (Figure 2b).



Notes: The figure shows climatological mean demand as a bold line over all years using a moving average over a window of 168h (resulting in the blank first week) as a line, the standard deviation range as an area ($mean \pm std\ dev$, dark green), the difference between the climatological minimum and maximum as an area using a moving average over a window of 24h (light green), and the regional difference between the minimum and maximum climatological mean normalized by the maximum in parenthesis. Each vertical axis is scaled to show its range if demand seasonality in this region was as pronounced as in France.

Figure 3: Demand seasonality across countries, which is particularly pronounced in France both in terms of level but also variance within winter months due to high shares of electrified heat.

In the pan-European copperplate scenario, droughts are notably less severe than in individual countries (lower drought mass), resulting in significantly reduced normalized storage needs. This is due to a geo-

graphical balancing effect, which spatially smooths renewable generation and demand patterns, thereby mitigating extreme droughts [30, 35].

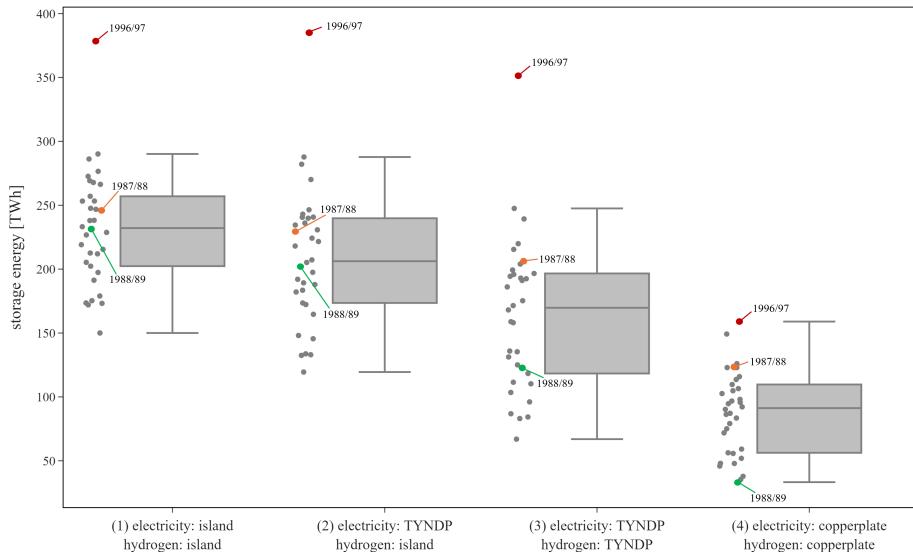
In the Supplementary Information, we discuss why the correlation between the most extreme winter drought event and the optimal long-duration storage size for the same year is not perfect (SI.4).

3.3. Long-duration storage needs decrease with geographical balancing

Interconnection provides spatial power system flexibility to cope with VRE droughts, which affects long-duration storage needs. Figure 4 illustrates how interconnection mitigates the need for long-duration storage. Scenario (1) shows the results if every country was an energy island, excluding the possibility of exchanging electricity or hydrogen with its neighbors to mitigate extreme renewable droughts. Here, an aggregated median (maximum) long-duration storage energy capacity of 232 (378) TWh is required across all modeled countries. This corresponds to around 4.7 (7.6)% of the yearly European electricity demand. Scenario (2) allows for policy-oriented TYNDP cross-border exchange of electricity, which reduces the median (maximum) long-duration storage energy capacity to 206 (385) TWh, or 4.2 (7.8)%. The slight increase in the maximum requirement is mainly driven by an increase in offshore wind generation in Belgium, which is transmitted to and stored in additional long-duration storage in the Netherlands, while long-duration storage energy capacity remains at its expansion limit in Belgium. Additionally including hydrogen exchange within policy-oriented limits in scenario (3) further decreases the median long-duration storage energy to 170 (351) TWh, or 3.4 (7.1)%. Finally, scenario (4) allows for an unconstrained exchange of electricity and hydrogen, rendering the lowest storage needs with a median value of 91 (159) TWh, corresponding to 1.8 (3.2)% of yearly electricity demand. The decreasing storage energy with increasing interconnection capacity is due to geographical balancing, which smooths storage-defining renewable droughts [30].

Storage results show a substantial degree of inter-annual variation. This is driven by differences in renewable energy droughts and demand patterns across years (compare Figure 3). The inter-annual variation increases in scenarios (2) and (3), which allow for policy-oriented geographical balancing compared to the island setting. This is because the correlation of storage-defining drought events in individual countries varies across space and time across weather years [30]. When drought events do not occur simultaneously across countries, a more pronounced geographical balancing can reduce long-duration storage needs, expanding the lower bound of the storage energy capacity range. The effect is even more pronounced when including cross-border exchange hydrogen in scenario (3). We find the lowest weather year variation in the copperplate scenario, in which all drought events are balanced to the fullest extent possible.

The year 1996/97 marks the period with the highest long-duration storage investments across all interconnection scenarios, which is in line with the most extreme drought in Europe that we find in renewable availability data (Figure SI.2). The reducing effect of geographical balancing via policy-oriented interconnection on total storage needs is limited. This is because storage-defining drought events in winter 1996/97 are strongly correlated and co-occurring (see teal boxes in Figure 5) and largely coincide with win-



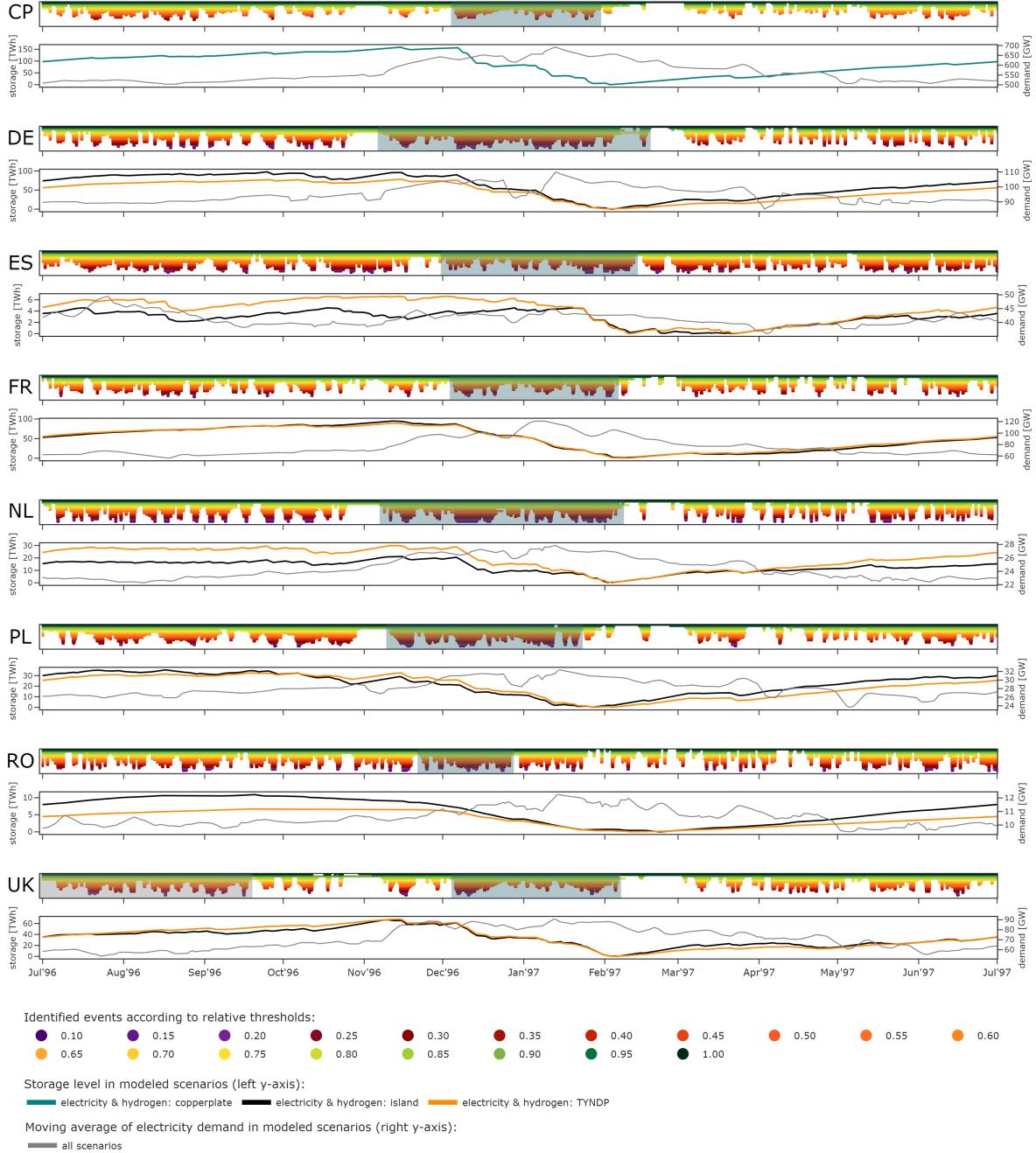
Notes: Each dot refers to one modeled weather year, which is modeled independently of other weather years. The year with the highest long-duration storage need is 1996/97 (red). The year that benefits most from rising interconnection capacity in terms of decreasing long-duration storage needs is 1988/89 (green). The year that benefits the least from increasing interconnection is 1987/88 (orange). Figure SI.7 illustrates the impact of interconnection on the ranking of weather years in terms of optimal long-duration storage energy.

Figure 4: Optimal long-duration storage energy capacity aggregated across all countries for all modeled weather years and interconnection scenarios.

ter demand peaks. In contrast, the unconstrained balancing in the copperplate scenario (4) substantially mitigates overall storage needs. In other years, the effects of interconnection may play out differently. For instance, geographical balancing has a particularly strong storage-mitigating effect in the year 1988/89, as the largest droughts in major countries hardly overlap and co-occur with high demand periods only to a limited extent (Figure SI.5). In contrast, the period 1987/88 seems less affected by interconnection. Its relative position in the ranking of years even slightly increases with increasing interconnection. This can be explained by a large temporal overlap of droughts in individual countries (Figure SI.6). Figure SI.7 additionally illustrates the change of weather year ranking as interconnection levels increase.

Figure 4 also indicates Europe's minimum need for long-duration storage capacity to cope with the Dunkelflaute. This can be inferred from scenario (4), which allows for unlimited exchange of electricity and hydrogen between countries. The results suggest that this "no-regret" level of storage investment amounts to 159 TWh or 3.2% of the yearly European electricity demand. This amount of long-duration storage is needed to balance the remaining energy deficit of the most extreme VRE drought in the data after unconstrained geographical balancing and cannot be further compensated by additional interconnection. Given policy-oriented interconnection levels in scenario (3), our analysis suggests that the need for long-duration storage capacities increases to 351 TWh, equivalent to 7.1% of the yearly European electricity demand. If the envisaged interconnection levels cannot be realized but remain at the current level, then long-duration storage needs will likely be even higher and range between the outcomes of scenarios (1) and (3).

licable here). See Grochowitdifferentp.org/article/10.108 for coping with extreme droughts8/1Figure 6



Notes: For each region, the figure illustrates identified drought patterns lasting longer than 12 hours across all color-coded thresholds (upper panel) and the most extreme drought events occurring in winter (teal boxes). For the UK, where the most extreme drought throughout the year occurs in summer, this event is additionally shown (gray box). The lower panels show exogenous demand profiles, which have been smoothed to highlight demand seasonality. They further display optimized storage state-of-charge levels for isolated countries modeled within the interconnection scenario (1), for policy-oriented interconnection levels in scenario (3), and the pan-European copperplate (CP) in scenario (4).

Figure 5: Drought events, electricity demand, and state-of-charge of long-duration storage in winter 1996/97 in countries with highest long-duration storage energy capacities.

illustrates the power sector operation for exemplary weeks in Germany and Spain for the weather year 1996/97. These optimized dispatch patterns reveal complex interactions between short-duration flexibility options such as batteries or pumped hydro storage and longer-duration flexibility options. The latter include hydrogen-based electricity storage, hydro reservoirs, and dispatchable bioenergy. These flexibility options differ in their cost structures. Short-duration flexibility options typically have relatively low power capacity costs but high energy capacity costs. As storage duration rises, this relation inverts. Electrolysis and gas turbines, used for long-duration storage charging and discharging, incur high power capacity costs, while long-duration energy capacity costs are substantially lower. When combining these flexibility options, we observe five effects in dispatch patterns that enable coping with extreme VRE droughts at the lowest possible cost.

First, electrolysis for long-duration storage charging typically occurs before but also within major renewable energy droughts (Figure 6a). In certain situations, short-duration battery storage cycles, i.e., it charges and subsequently discharges, while electrolyzers are continuously running. Similarly, bioenergy generation or hydro reservoirs may generate electricity in such long-duration charging periods. This specific operation leverages the lower-cost power capacity of different flexibility options to increase electrolyzer full-load hours by allowing them to operate not only in negative but also in positive residual load situations, which minimizes electrolysis capacity needs.

Second, battery cycling may conversely also occur in periods of uninterrupted discharging of long-duration storage, i.e., while hydrogen gas turbines generate electricity (e.g., on December 12 in Figure 6b). Charging batteries with electricity that is discharged from hydrogen-based storage may appear counter-intuitive as it incurs additional energy losses from conversion. Yet, this combined use of different flexibility options minimizes the hydrogen gas turbine capacity required during peak residual load events. The battery capacities do not incur additional investment costs here, as they are anyway required for diurnal balancing in other periods of the year. In other words, long-duration storage may provide all the energy capacity needed to cope with a renewable drought but not necessarily all the power capacity. Similarly, shorter-duration storage temporally shifts renewable surplus to avoid additional hydrogen gas turbine capacity investments (e.g., battery and pumped hydro charge on December 16 and discharge on December 17 and 18 in Figure 6b).

Third, short-duration flexibility options are used to balance brief events of renewable surplus generation within longer drought events. In such cases, the discharging of long-duration storage is interrupted, and batteries and pumped hydro storage are used instead for short-duration balancing (e.g., visible on December 16, 22, 25, or 26 in Figure 6b). The model favors shorter-duration storage over hydrogen-based storage because of lower roundtrip energy losses, which could be interpreted as a “merit order” of storage technologies.

Fourth, in countries with less pronounced solar seasonality in winter and significant reservoir capacity, such as Spain, optimal battery discharge capacity is relatively large compared to hydrogen gas turbine capacity.

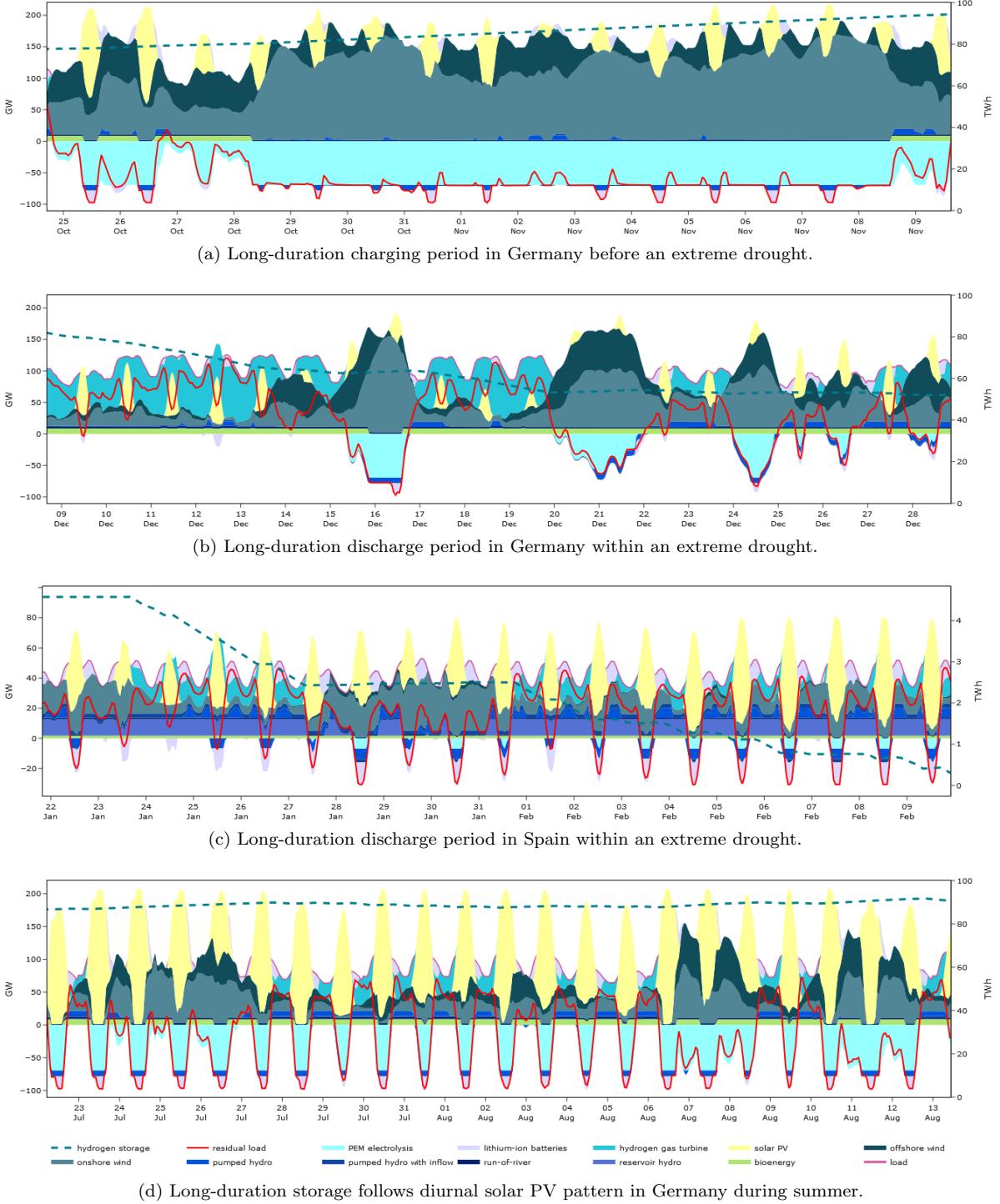


Figure 6: Optimized power sector operation in Germany and Spain for the weather year 1996/97. The positive part of the left y-axis relates to generation and storage discharge, and its negative part to electricity demand and storage charge. The right y-axis refers to the long-duration storage state-of-charge. For illustration, we focus on scenarios excluding cross-border exchange of electricity or hydrogen.

During extreme drought periods, long-duration storage discharge enables battery charging before and after PV peaks, even in positive residual load periods (e.g., visible on January 24 in Figure 6c). Although this operation incurs high conversion losses, it leverages lower-cost power capacity of short-duration flexibility options that is anyway required to balance diurnal PV variations in other times of the year, which minimizes higher-cost long-duration storage discharge capacity.

Finally, long-duration storage may not only be used in periods of extended renewable energy droughts but also for diurnal cycling in summer (Figure 6d). Hydrogen-based storage integrates solar PV surplus energy, which reduces the need for short-duration battery capacity that otherwise would be required for this purpose. Importantly, optimal long-duration storage capacity is not defined by these diurnal variability patterns in summer, but rather by balancing needs for major renewable winter droughts. In other words, the long-duration storage capacity required to cope with winter droughts has repercussions on the optimal capacity and dispatch decisions that allow for dealing with summer-time solar PV variability.

3.4. Sensitivity analyses

So far, we only allowed for firm and variable renewable technologies. However, some European countries consider nuclear power a valid decarbonization option. To reflect country-specific energy policy strategies, we thus include nuclear power in Finland, France, Romania, Slovakia, and the UK in a sensitivity run, totaling 24 GW based on the assumptions of the TYNDP 2022 [85]. This firm generation capacity can continuously provide power during extreme renewable drought events. Yet, this reduces the need for long-duration storage energy capacity across all investigated interconnection scenarios only to a minor extent (Figure 7). Without geographical balancing in scenario (1), nuclear power reduces the aggregated median (maximum) long-duration storage energy capacity by 4.4 (5.9)%. With policy-oriented cross-border exchange of electricity in scenario (2) or electricity and hydrogen in scenario (3), the mitigating effect on the aggregated median (maximum) storage energy capacity is slightly larger with 6.4 (6.8)% or 8.1 (6.7)%, respectively. This is because the additional firm generation mitigates renewable droughts both domestically and in other countries. This mitigating effect is less pronounced under the assumption of unconstrained geographical balancing in scenario (4), with a reduction of the mean by 2.7%, and maximum storage energy even slightly increases by 0.5%. In this case, nuclear power disproportionately displaces bioenergy, i.e., one gigawatt of nuclear power substitutes more than one gigawatt of bioenergy. Electricity generation from bioenergy, which serves as a renewable baseload technology in the previous scenarios, is therefore only partially replaced by nuclear power during renewable droughts, which in turn can necessitate a slightly higher long-duration storage energy capacity for coping with these events. Long-duration storage further remains necessary to continuously meet the flat hydrogen demand from coupled sectors (see SI.1).

While limited in near-term scalability [7], other firm zero-emission generation technologies may potentially become viable in the longer run, such as advanced nuclear fission or fusion or advanced geothermal power generation. Such technologies are expected to have very high capital costs but low operational costs,

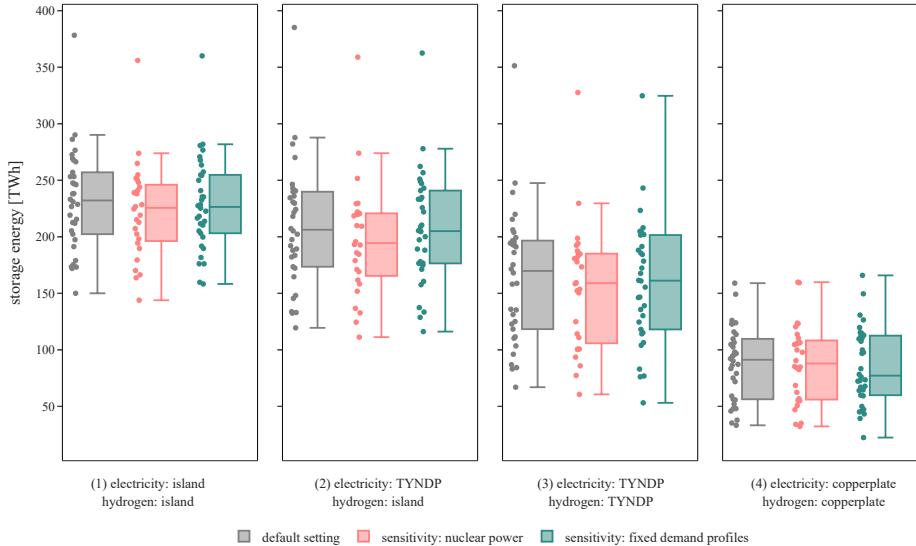
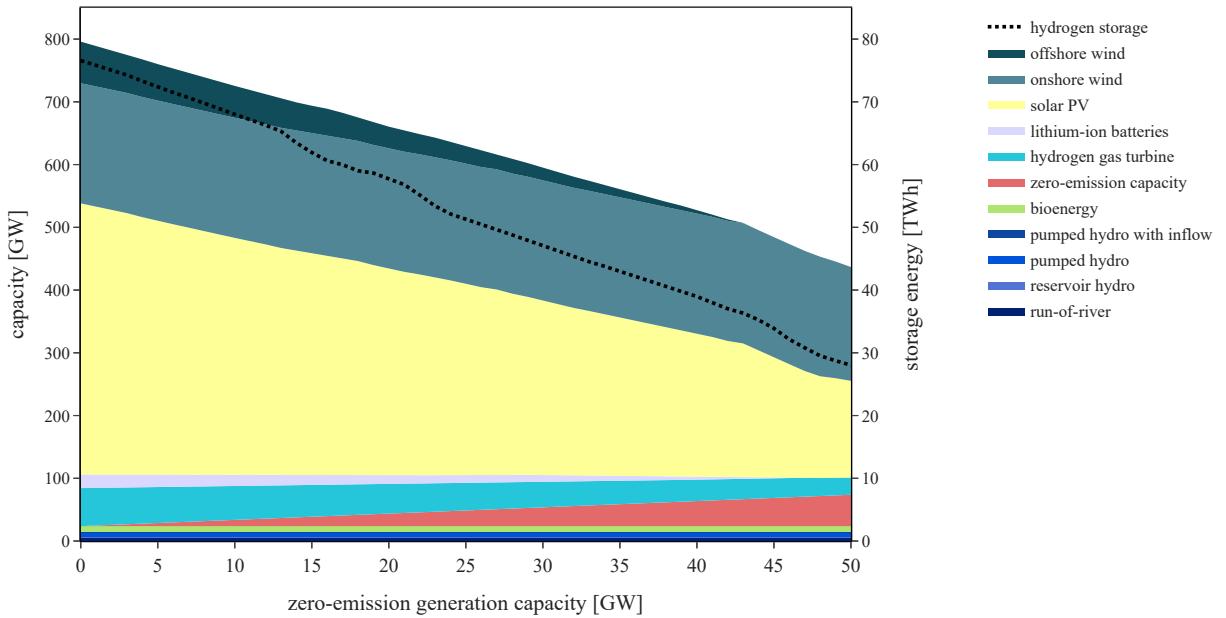


Figure 7: Optimal long-duration storage energy capacity aggregated across all countries for all modeled weather years and interconnection scenarios.

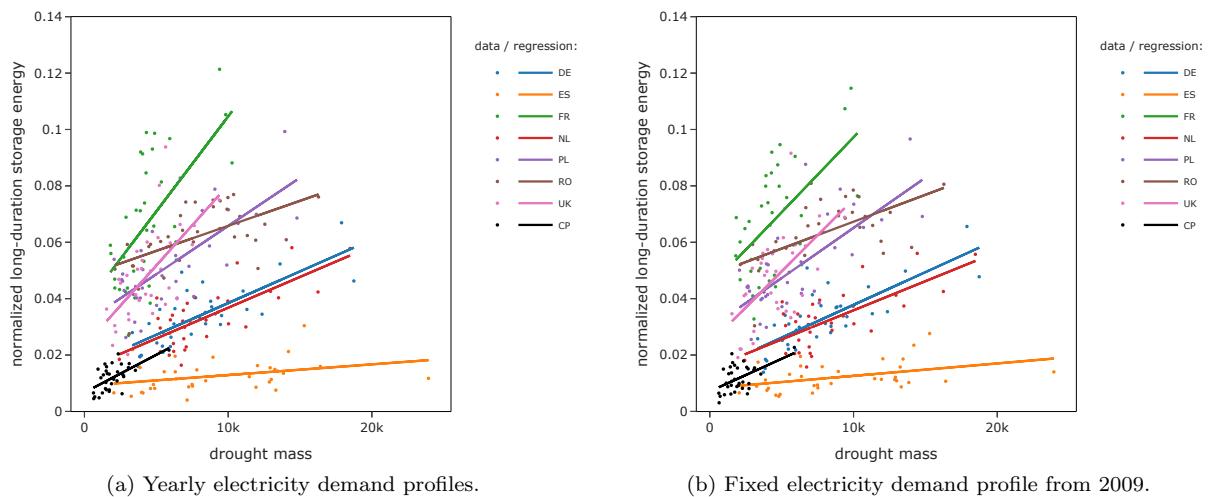
which implies that they would optimally operate at very high full-load hours. Based on the weather year 1996/97, which includes a very pronounced renewable drought in many European countries, we analyze the impact of a generic dispatchable zero-emission technology on long-duration storage for the illustrative example of Germany, modeled as an energy island. In a series of 51 model runs, we iteratively increase the exogenous generation capacity of the zero-emission capacity by 1 GW increments as dispatch and investment decisions of all other generation and storage technologies remain endogenous. The firm zero-emission technology can continuously generate electricity not only during extreme droughts but also throughout the entire modeled weather year. This reduces the reliance on variable wind and solar power, which decreases the need for system flexibility. Figure 8 illustrates these substitution effects. In addition to disproportionately displacing VRE capacity due to higher full-load hours, the increasing zero-emission generation capacity also reduces the need for battery storage, hydrogen gas turbines, and long-duration storage energy capacity. Yet, long-duration storage remains required as long as variable renewables are still part of the energy mix.

In additional sensitivity analyses, we investigate the impact of the inter-annual variability of electricity demand on long-duration storage needs. This is of interest because model-based energy system studies often use demand data for only a limited number of years or even a single year. To isolate this effect, we model the entire set of weather years as above but do not use the demand profiles of the respective weather years, but always the one from 2009/2010, leaning on the TYNDP 2022 methodology. Comparing the correlation between winter droughts and long-duration storage needs from the original runs with annually varying demand profiles (Figure 9a) and the sensitivity runs with fixed demand profiles (Figure 9b) reveals only minor differences in regression coefficients and intercepts. This indicates that inter-annual demand variations have a negligible impact on the storage-defining effect of extreme renewable droughts.



Notes: We limit the expansion of solar PV as well as on- and offshore wind according to the upper bounds of the TYNDDP 2024, while we remove the lower expansion bounds. Section SI.6 elaborates on the non-steady decline in long-duration storage energy.

Figure 8: Sensitivity of optimal wind and solar capacity as well as short- and long-duration flexibility options to an increasing zero-emission generation capacity.



Notes: For comparison, we normalized the optimal storage energy by annual demand for electricity (including electrified heating) and hydrogen. For illustration, countries with storage energy below 5 TWh or storage energy at potential are excluded.

Figure 9: Correlation of winter drought mass and optimal long-duration storage energy normalized by annual demand for electricity and hydrogen across years.

4. Discussion

4.1. Summary and conclusions

This paper analyzes the impact of renewable energy droughts on investment and operational decisions of storage and generation technologies, particularly on long-duration energy storage, in a future renewable European power system. To this end, we combine a renewable time series analysis for VRE drought identification with power sector modeling to analyze scenarios with different interconnection levels across European countries for 36 weather years.

Our analysis yields several key insights and conclusions. Extreme renewable energy droughts, which may last several weeks or even months, define operational and investment needs for long-duration storage in a European power sector with high shares of wind and solar power. Major discharge periods of long-duration storage coincide with the most pronounced drought periods identified in the data. Further, our results reveal a positive correlation between extreme drought events and optimal storage energy capacity investments for many European countries and weather years. Firm renewable energy sources such as hydro reservoirs or bioenergy mitigate long-duration storage needs for dealing with extreme droughts while co-occurring high-demand periods exacerbate them.

Interconnection among European countries can significantly reduce the need for long-duration energy storage. Extending previous literature [35], we show that this general finding also holds in settings with extreme renewable energy droughts. Yet, the storage-mitigating effect of interconnection for dealing with the most pronounced renewable droughts is limited. As inferred from our copperplate scenario, the storage capacity required for coping with the most extreme events in the data (particularly in winter 1996/97) could only be substantially reduced in scenarios with interconnection levels far beyond envisaged grid expansion plans. In contrast, policy-oriented interconnection levels, as foreseen in the TYNDP scenarios, mitigate the storage needs for extreme drought events only to a limited extent. Yet, additional cross-border exchange of renewable hydrogen, as planned in the European Union, contributes to reducing long-duration storage needs.

Thus, a sizeable need for long-duration electricity storage will remain in a fully renewable European power sector, irrespective of the extent of interconnection. Even under the assumption of a perfectly interconnected Europe, coping with the most pronounced drought in the data would require 159 TWh of long-duration storage, corresponding to around 3% of yearly electric load. This storage capacity can be interpreted as a lower boundary of what a fully renewable European energy system requires and could serve as a “no-regret” target for system planning. In more policy-relevant TYNDP interconnection scenarios between European countries, long-duration storage needs substantially increase to 351 TWh, or more than 7% of yearly European electricity demand. Our results extend previous analyses that focused on droughts in single countries, such as Germany, where long-duration storage capacities of 9% [69] or 10% [60] of annual electricity demand are required for dealing with extreme drought events. Realizing such energy capacity levels appears technically feasible, considering that around 1700 TWh of natural gas storage is

currently installed in Europe [102], and taking into account that hydrogen has a lower volumetric energy density compared to methane. Yet, so far there is very limited experience with converting existing gas storage to hydrogen or building new underground hydrogen storage [101]. The same applies to hydrogen grids as well as hydrogen generation and re-conversion infrastructure.

Importantly, large-scale adoption of hydrogen-based long-duration storage, comprising electrolyzers, caverns, and hydrogen turbines for reconversion, will likely have long lead times because of supply chain and permitting bottlenecks [103, 104]. Consequently, system planners and policy-makers should consider early action to enable rapid scaling for realizing the hydrogen storage investments determined here. Further, the maximum long-duration storage need in Europe, driven by the most extreme renewable drought in the winter of 1996/97, exceeds the next highest storage need found for the weather year 1984/85 by 42%. Market actors are unlikely to invest in such rarely utilized long-duration storage capacity without additional deployment incentives. Accordingly, targeted support or capacity mechanisms may be required to ensure sufficient storage capacity for coping with rare and extreme droughts.

We also observe complex interactions of long-duration storage with short-duration batteries and other flexibility options. The latter can mitigate long-duration charging and discharging capacities to some extent. We also show that long-duration storage does not continuously discharge during prolonged drought periods, and instead, shorter-duration flexibility options are used. Further, hydrogen storage needed for coping with winter droughts can complement batteries in balancing diurnal PV variability in summer. Detailed numerical power sector modeling with an adequate representation of different flexibility technologies and a high temporal resolution appears indispensable for analyzing such interactions. System planners should consider these potential interactions of a wide range of complementary flexibility options for realizing least-cost renewable energy systems.

Next, the selection of weather years has a notable impact on long-duration storage use in energy system models, which confirms previous research [29, 75, 80, 105]. Different weather years result in widely varying optimal long-duration storage investments, particularly in scenarios with constrained interconnection. These inter-annual variations emphasize the significance of accounting for extreme renewable droughts when planning renewable energy systems and particularly for long-duration storage sizing.

However, due to computational limitations, many policy-relevant studies rely on only one or a limited set of weather years. For instance, the TYNDP 2022 [18], a strategic decarbonization report for the European power sector, draws on three weather years (1995, 2008, and 2009) for its long-term scenarios for 2050. Our analysis shows that the optimal long-duration storage capacity considering TYNDP interconnection levels in the corresponding summer-to-summer weather years (1994/95, 1995/96, 2007/08, 2008/09, and 2009/10) ranges from 103 to 239 TWh. Notably, the storage capacity required to balance the most extreme drought in winter 1996/97 is 47% higher than this range's upper bound. This underscores the importance of considering multiple weather years for identifying weather-resilient system configurations, particularly those that include the most pronounced drought events.

To select such years, we propose using VRE drought analysis based on renewable availability time series and multi-threshold indicators such as the drought mass metric. Importantly, respective time series analyses should rely on multiple drought thresholds and account for sequences of contiguous droughts with varying severity to adequately capture the most extreme events [22, 30].

For Europe, the power sector impacts of VRE droughts are most pronounced in winter, particularly in the winter of 1996/97 [30]. Consequently, a summer-to-summer or multi-annual planning horizon for energy system modeling is more suitable to capture storage-defining drought events compared to using single calendar years. We argue that our summer-to-summer modeling approach better captures the effects of compound drought events such as the ones in late 1996 and early 1997, as compared to models using single calendar years, such as [80].

Sensitivity analyses confirm the robustness of our findings in case moderate levels of firm generation capacity are present. Moderate, policy-oriented levels of nuclear power in the capacity mix of five European countries mitigate long-duration storage needs across Europe only to a minimal extent, particularly for weather years with very severe renewable droughts. This leads to the conclusion that moderate levels of nuclear power would hardly reduce the need for flexibility options for coping with extreme drought events. However, its role in a net-zero European energy system remains contentious due to scalability challenges, exceptionally long construction times, high uncertainty in final investment costs, as evident in ongoing expansion projects in Europe and globally, and the economic, environmental, and societal challenges of nuclear waste management. Abstracting from these implementation barriers, and conceptually going beyond nuclear power, our sensitivity analysis for a Germany-only scenario illustrates that higher capacities of firm low- or zero-emission generation technologies could reduce long-duration storage requirements to a larger extent. Still, long-duration storage needs remain substantial, even in hypothetical scenarios with firm zero-emission capacity that by far exceed the nuclear generation capacity ever realized in Germany.

Finally, there is no consensus on the definition of variable renewable energy droughts [22]. In the energy policy debate, events lasting from just a few hours to one or two weeks have been labeled as Dunkelflaute [13, 19, 20, 106]. Based on our analysis, we propose refining the Dunkelflaute notion to focus on events with the most significant implications for long-duration power sector flexibility: extended (winter) periods where renewable energy falls short of electricity demand, which ultimately define the energy capacity and the operation of long-duration storage. We suggest not using the term Dunkelflaute for very short periods of low wind and solar availability, especially not for a few hours within a day. While such shorter events will become more frequent as VRE penetration increases [30], dealing with them particularly requires short-duration flexibility options that rather focus on power and not on energy, such as battery storage. Yet, such short-duration technologies are likely to be inherently necessary for systems with high shares of wind and solar to balance regular diurnal demand and solar variations.

4.2. Limitations

Our analysis has several limitations. We briefly discuss their qualitative effects on our main results in the following. First, space heating will likely be electrified to a substantial extent in future European energy scenarios [107]. This will not only increase annual electricity demand but also lead to a more pronounced demand seasonality due to substantially higher (peak) demand in winter. While we account for the additional electricity demand, our demand time series only have a moderately seasonal profile as expected for 2025 (see Section 2.4). Complementary model runs indicate that demand profiles with more pronounced seasonality lead to significantly higher long-duration electricity storage needs. These, in turn, could be mitigated by long-duration thermal energy storage on district or even building levels. However, interactions of different types of thermal storage, heating technologies, and building renovation with the power sector are complex [97, 108] and beyond the scope of this paper.

Next, our analysis excludes industrial and commercial load shifting, load shedding as well as optimized grid interactions of battery-electric vehicles. While these flexibility options would generally enhance system flexibility, their impact on long-duration energy needs is likely limited because of their limited duration. We further abstract from conventional backup generation such as gas or oil turbines, which may provide a cost-efficient measure to avoid unmet electricity demand at limited emissions while decreasing long-duration storage needs [80].

Similarly, we do not consider other long-duration storage technologies than hydrogen caverns in combination with electrolyzers and hydrogen turbines. For example, methanol-based long-duration storage in combination with Allam cycle turbines has recently been discussed as a potential alternative [105]. This technology does not depend on highly localized underground sites but allows for aboveground storage that can generally be placed anywhere [100, 101], which could lead to spatial redistribution of optimal storage capacity. Further, if this alternative storage technology came with higher roundtrip losses or with lower costs than assumed here for hydrogen-based long-duration storage, optimal storage capacities aggregated across all countries are likely to increase compared to our results.

4.3. Future research

Some of these limitations merit future research. In particular, future work could explore the effects of additional electricity demand in winter, driven by more pronounced electrification of space heating. In such a setting, low temperatures compounding extreme VRE droughts would be of particular interest. A promising extension of our research design would be to investigate how various forms of thermal energy storage and heating technologies in combination with different levels of building renovation [97, 108, 109] impact long-duration electricity storage needs, and how parameter assumptions like investment costs or standing losses influence results.

Next, we propose investigating the effects of different time horizons for energy modeling, ranging from single years to several years [29], yet with a particular focus on drought events. This also includes quantifying the distortions of modeling either summer-to-summer periods, as done in our study, or winter-to-winter

periods. For multi-year analyses, considering imperfect foresight for long-duration storage operation may offer complementary insights.

Finally, it appears desirable to explore the impact of future changes in renewable energy droughts and storage needs driven by climate change. This strand of research would benefit from interdisciplinary collaboration at the intersection of climate and energy modeling [83].

Author Contributions

Martin Kittel: Conceptualization (lead), methodology, model development (lead), software (lead), investigation (lead), data curation (equal), visualization, writing - original draft (equal), review and editing (lead). **Alexander Roth:** Conceptualization (support), software (support), investigation (support), data curation (equal), writing - original draft (equal), review and editing (support). **Wolf-Peter Schill:** Conceptualization (support), model development (support), investigation (support), writing - original draft (support), writing - review and editing (support), project acquisition and administration.

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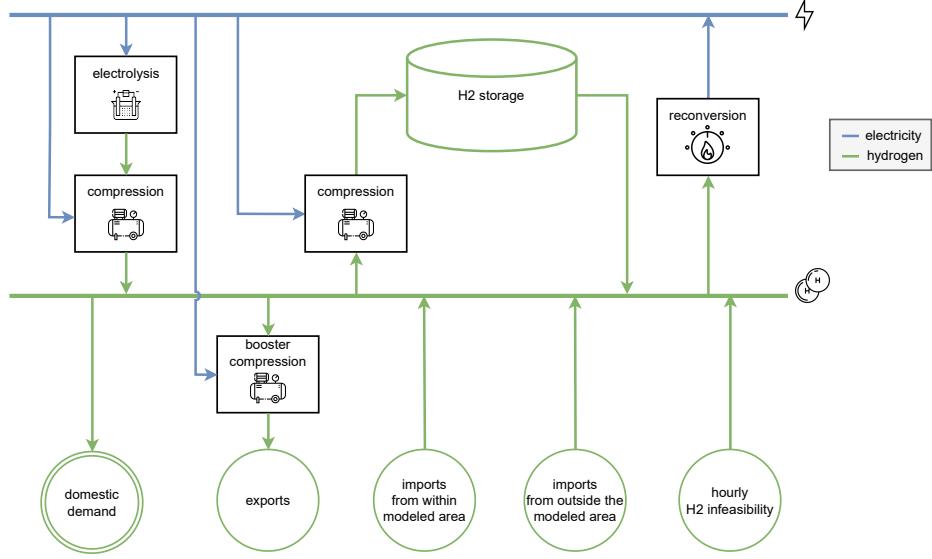


Figure SI.1: Schematic overview of the hydrogen module in DIETER.

Supplementary information

SI.1. Formal definition of the hydrogen module

We present the model equations implementing the generation, storage, and transport of renewable hydrogen technologies as well as its re-conversion to electricity in DIETER in the following (Figure SI.1). For simplicity, we use only a single technology for each of these features. Endogenous model variables are given in capital letters and exogenous parameters in lowercase. We denote the electricity demand for the production of green hydrogen production $G_{n,ely,t}^{ely}$ in time step t and country n . Each electrolysis technology ely has a specific efficiency $\eta_{n,ely}^{ely} < 1$ and a flat availability $avail_{n,ely}^{ely}$. The electricity demand of an electrolyzer must not exceed its generation capacity $N_{n,ely}^{ely}$:

$$G_{n,ely,t}^{ely} \leq avail_{n,ely}^{ely} * N_{n,ely}^{ely} \quad (1)$$

The produced hydrogen is compressed to a system-wide pressure level, constrained by the compressor capacity $N_{n,ely}^{comp,ely}$ with an efficiency $\eta_{n,ely}^{comp,ely} < 1$, and fed into a hydrogen grid that links generation, storage, and re-conversion units as well as import and export pipelines.

$$\eta_{n,ely}^{ely} * G_{n,ely,t}^{ely} \leq avail_{n,ely}^{ely} * N_{n,ely}^{comp,ely} \quad (2)$$

Using a storage technology sto , hydrogen can be stored. Hydrogen that is added to storage $STO_{n,sto,t}^{in}$ has to be compressed. Compression losses are reflected in the charging efficiency $\eta_{n,sto}^{comp,in} < 1$. A storage energy balance links the storage state-of-charge $STO_{n,sto}^L$ inter-temporally. While there might be self-discharge $\eta_{n,sto}^{sto,self} < 1$, we assume storage discharge $STO_{n,sto,t}^{out}$ to be lossless due to the high-pressure level.

$$STO_{n,sto,t}^L = eta_{n,sto}^{sto,self} * STO_{n,sto,t-1}^L + eta_{n,sto}^{comp,in} * STO_{n,sto,t}^{in} - STO_{n,sto,t}^{out} \quad (3)$$

To avoid free lunch, we require that the storage levels are equal in the first time step $t = 1$ and last time step $t = T$:

$$STO_{n,sto,1}^L = eta_{n,sto}^{sto,self} * STO_{n,sto}^{L,initial,last} + eta_{n,sto}^{comp,in} * STO_{n,sto,1}^{in} - STO_{n,sto,1}^{out} \quad (4)$$

$$STO_{n,sto,T}^L = STO_{n,sto}^{L,initial,last} \quad (5)$$

Suppose $avail_{n,sto}^{sto}$ is the flat availability of each storage technology sto , the storage level cannot exceed the installed storage energy capacity $N_{n,sto}^{sto}$:

$$STO_{n,sto,t}^L \leq avail_{n,sto}^{sto} * N_{n,sto}^{sto} \quad (6)$$

To maintain a minimum pressure level required for the cushion gas, we impose a minimum filling state $\phi_{n,sto}^{sto,min} < 1$:

$$STO_{n,sto,t}^L \geq \phi_{n,sto}^{sto,min} * avail_{n,sto}^{sto} * N_{n,sto}^{sto} \quad (7)$$

Note that in this paper, we abstract from minimum filling levels to focus on required the working gas, i.e., $\phi_{n,sto}^{sto,min} = 0$. Hourly storage charging is constrained by the compression capacity $N_{n,sto}^{comp,st0}$:

$$STO_{n,sto,t}^{in} \leq avail_{n,sto}^{sto} * N_{n,sto}^{comp,st0} \quad (8)$$

Hourly storage discharge is constrained by a maximum discharge rate $\phi_{n,sto}^{sto,max} < 1$:

$$STO_{n,sto,t}^{out} \leq \phi_{n,sto}^{sto,max} * avail_{n,sto}^{sto} * N_{n,sto}^{sto} \quad (9)$$

Hydrogen can be re-converted to electricity. Suppose $avail_{n,recon}^{recon}$ is the flat availability of the re-conversion technology $recon$ and $\eta_{n,recon}^{recon} < 1$ the conversion efficiency, the electricity output $G_{n,recon,t}^{recon}$ is then limited by capacity of the re-conversion unit $N_{n,recon}^{recon}$:

$$G_{n,recon,t}^{recon} \leq avail_{n,recon}^{recon} * N_{n,recon}^{recon} \quad (10)$$

Hydrogen can be generated domestically, imported from other world regions, or exchanged hydrogen across

modeled countries based on a simple cross-border transport model. Hydrogen flows are denoted $F_{p,t}$. The set p consists of all pipelines within the modeled area and those import pathways $path$ from outside the modeled area. The latter include pipeline-based imports from North Africa or Ukraine and ship-based imports from the world market. A hydrogen flow may not exceed its pipeline or shipping capacity N_p^{trans} :

$$F_{p,t} \leq N_p^{trans} \quad (11)$$

We assume constant hydrogen imports IM_{path}^{const} from outside the modeled area:

$$F_{path,t} = IM_{path}^{const} \quad (12)$$

The sum of all imports accumulates to IM_{path} :

$$\sum_t F_{path,t} = IM_{path} \quad (13)$$

To avoid infeasibility, we allow for slack hydrogen generation $INFES_{n,t}$ which needs to equal $INFES_n^{const}$ in all time steps to emulate constant imports in settings with disabled hydrogen flows:

$$INFES_{n,t} = INFES_n^{const} \quad (14)$$

Lines and countries are linked via the grid and import pathways, which are represented by the directed incidence matrices $inc_{p,n}^{import}$ and $inc_{p,n}^{export}$. Exports incur losses, represented by the transport efficiency $\eta_p^{trans} < 1$. The model considers a hydrogen demand for applications in industry, transport, or heat, which leans on TYNPD 2022 (scenario Distributed Energy). We assume this exogenous demand d_t to be constant in each time step. The hydrogen balance of each country n ensures that the demand is met in each time step:

$$\begin{aligned} d_t^{h2} + \sum_{sto} STO_{n,sto,t}^{in} + \sum_{recon} \frac{G_{n,recon,t}^{recon}}{\eta_{n,recon}} + \sum_p inc_{p,n}^{export} * \frac{F_{p,t}}{\eta_p^{trans}} \\ = \sum_{ely} \eta_{n,ely}^{ely} * \eta_{n,ely}^{comp,ely} * G_{n,ely,t}^{ely} + \sum_{sto} STO_{n,sto,t}^{out} + \sum_p inc_{p,n}^{import} * F_{p,t} + INFES_{n,t}. \end{aligned} \quad (15)$$

The hydrogen grid is linked to the electricity grid through the electricity demand for electrolysis $G_{n,ely,t}^{ely}$, hydrogen compression after electrolysis $d_{n,ely}^{comp,ely}$ for injecting into the hydrogen grid, hydrogen compression for injection into storage $d_{n,sto}^{comp,sto}$, and hydrogen booster compression for exporting pipelines $d_{n,p}^{comp,trans}$. For this, we add (16) to the demand and (17) to the supply side of the electricity balance of

each country n , respectively. The latter is documented in Zerrahn and Schill [24]:

$$\dots + \sum_{ely} (1 + \eta_{n,ely}^{ely} * d_{n,ely}^{comp,ely}) * G_{n,ely,t}^{ely} + \sum_{sto} d_{n,sto}^{comp,sto} * STO_{n,sto,t}^{in} + \sum_p d_{n,p}^{comp,trans} * inc_{p,n}^{export} * \frac{F_{p,t}}{\eta_p^{trans}} \quad (16)$$

$$\dots + \sum_{recon} G_{n,recon,t}^{recon} \quad (17)$$

The model endogenously determines electrolysis, storage, compression, and re-conversion capacity and operation. The operational decisions for hydrogen transport are also endogenous, while we assume exogenous transport capacities. Suppose $c_{n,sto}^{var,sto}$ are the operational costs for storage charging, $c_{n,recon}^{var,recon}$ the operational costs for re-conversion, c_{path}^{import} the costs for importing hydrogen from outside the modeled area. To avoid infeasibilities, we allow unspecified imports of hydrogen incurring the costs c^{infes} (here at prohibitively high 500 EUR/MWh_{ch}). Suppose further c_n^{oc} and c_n^{fix} are the overnight and fixed investment costs, we impose them on the capacity of electrolysis technology ely , compression capacity after electrolysis $comp,ely$, compression capacity for storage injection $comp,sto$, energy capacity of storage technology sto , and capacity of re-conversion technology $recon$. We add these operational (18) and investment costs (19) to the model's optimization function, which minimizes total system costs. The latter is documented in Zerrahn and Schill [24]:

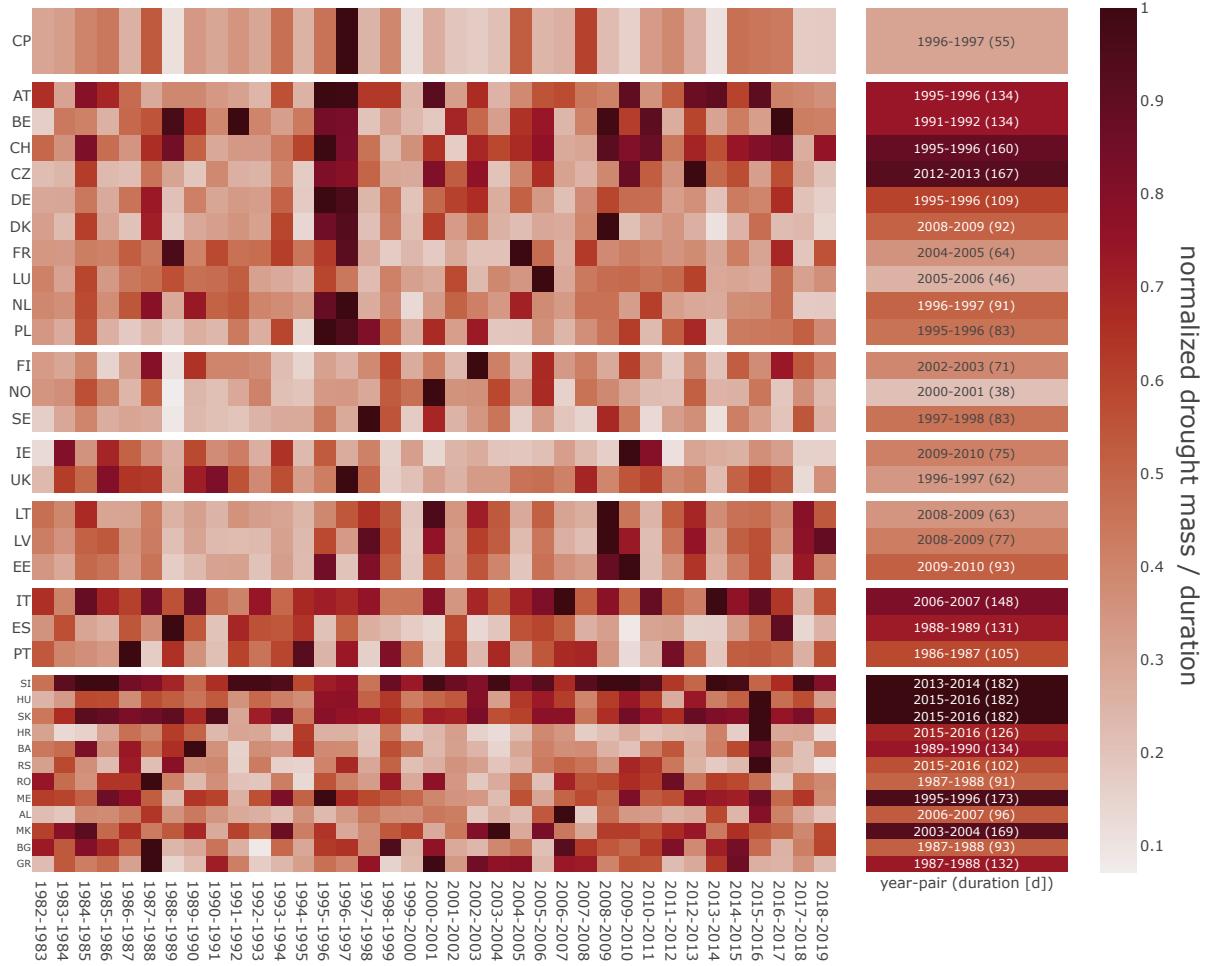
$$\dots + \sum_{n,sto,t} c_{n,sto}^{var,sto} * STO_{n,sto,t}^{in} + \sum_{n,recon,t} c_{n,recon}^{var,recon} * G_{n,recon,t}^{recon} + \sum_{path} c_{path}^{import} * IM_{path} + \sum_{n,t} c^{infes} * INFES_{n,t} \quad (18)$$

$$\begin{aligned} & \dots + \sum_{n,ely} (c_{n,ely}^{oc,ely} + c_{n,ely}^{fix,ely}) * N_{n,ely}^{ely} + \sum_{n,ely} (c_{n,ely}^{oc,comp,ely} + c_{n,ely}^{fix,comp,ely}) * N_{n,ely}^{comp,ely} \\ & + \sum_{n,sto} (c_{n,sto}^{oc,comp,sto} + c_{n,sto}^{fix,comp,sto}) * N_{n,sto}^{comp,sto} + \sum_{n,sto} (c_{n,sto}^{oc,sto} + c_{n,sto}^{fix,sto}) * N_{n,sto}^{sto} \\ & + \sum_{n,recon} (c_{n,recon}^{oc,recon} + c_{n,recon}^{fix,recon}) * N_{n,recon}^{recon} \end{aligned} \quad (19)$$

SI.2. Additional drought mass illustration

The duration and severity of most extreme winter droughts captured by the drought mass metric varies significantly across years and countries (Figure SI.2). Assuming perfect interconnection between all European countries, the most extreme event in the data occurred in the winter of 1996/97 and lasted 55 days. This European super drought was caused by pronounced and temporally overlapping events in many, yet not all, European countries (Figure 5). Hence, even during this extreme event, geographical balancing

remains possible to a limited extent. It is therefore substantially shorter than the most extreme droughts in nearly all countries when considered an energy island. Applying the drought mass metric to individual countries, we find the longest winter events in Eastern and Southern Europe. Further, smaller countries such as Slovenia (182 days, 2013/14) or Slovakia (182 days, 2015/16) tend to have longer extreme droughts than larger countries such as France (64 days, 2004/05), Sweden (83 days, 1997/98), Germany (109 days, 1995/96), or Spain (131 days, 1988/89). This is because smaller countries benefit less from geographical balancing within their borders.



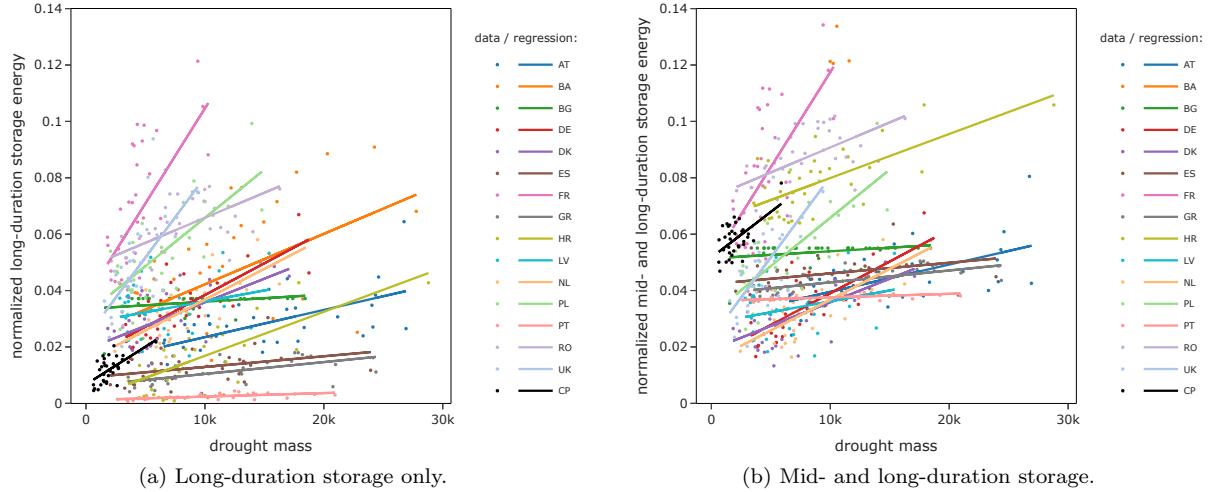
Notes: For each country or the European copperplate in the left panel, drought mass scores are normalized using the row-specific maximum. The colors of the right panel indicate the maximum duration of the event with the highest drought mass score normalized by the column-specific maximum, i.e., the maximum duration across all countries. The right panel also provides the year-pair with the most severe events as identified by the drought mass score per row and its corresponding duration in days.

Figure SI.2: Drought mass of identified most extreme winter drought events.

SI.3. Additional illustrations of the correlation between renewable droughts and long-duration storage energy

Figure SI.3 compares the correlation between winter droughts and long-duration storage needs, considering either long-duration storage only, or hydro and long-duration storage technologies combined. Including the latter in the regression shows a substantial level effect for countries with low regression coefficients,

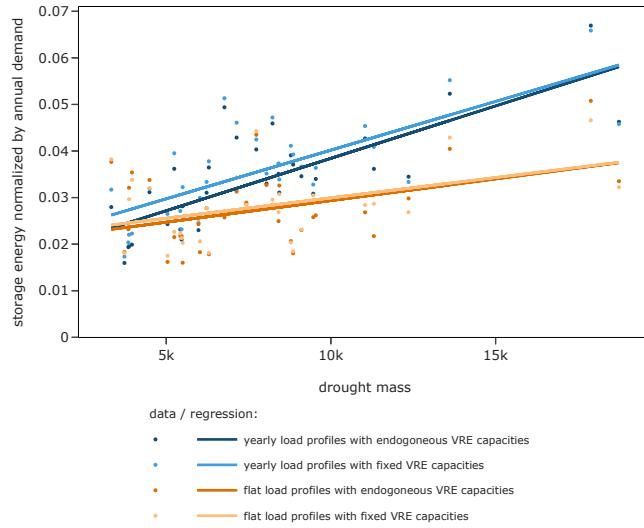
i.e., low sensitivity of long-duration storage needs to increasingly severe droughts, visible by the upward shift of the respective regression lines in Figure SI.3b compared to Figure SI.3a. This indicates that mid-term flexibility options can substitute long-duration storage needs for dealing with extreme droughts to a significant extent.



Notes: For comparison, we normalized the optimal storage energy by annual demand for electricity (including electrified heating) and hydrogen. For illustration, countries with negligible storage energy or storage energy at potential are excluded.

Figure SI.3: Correlation of winter drought mass and different types of storage energy normalized by annual demand for electricity and hydrogen across years.

Figure SI.4 shows additional regression results for a complementary Germany-only setting.



Notes: For comparison, we normalized the optimal storage energy by annual demand for electricity (including electrified heating) and hydrogen. The renewable portfolio assumptions of the scenarios with fixed VRE capacities align with those used for the time series-based VRE drought analysis. In contrast, the scenarios with endogenous VRE capacities are optimized by our power sector model.

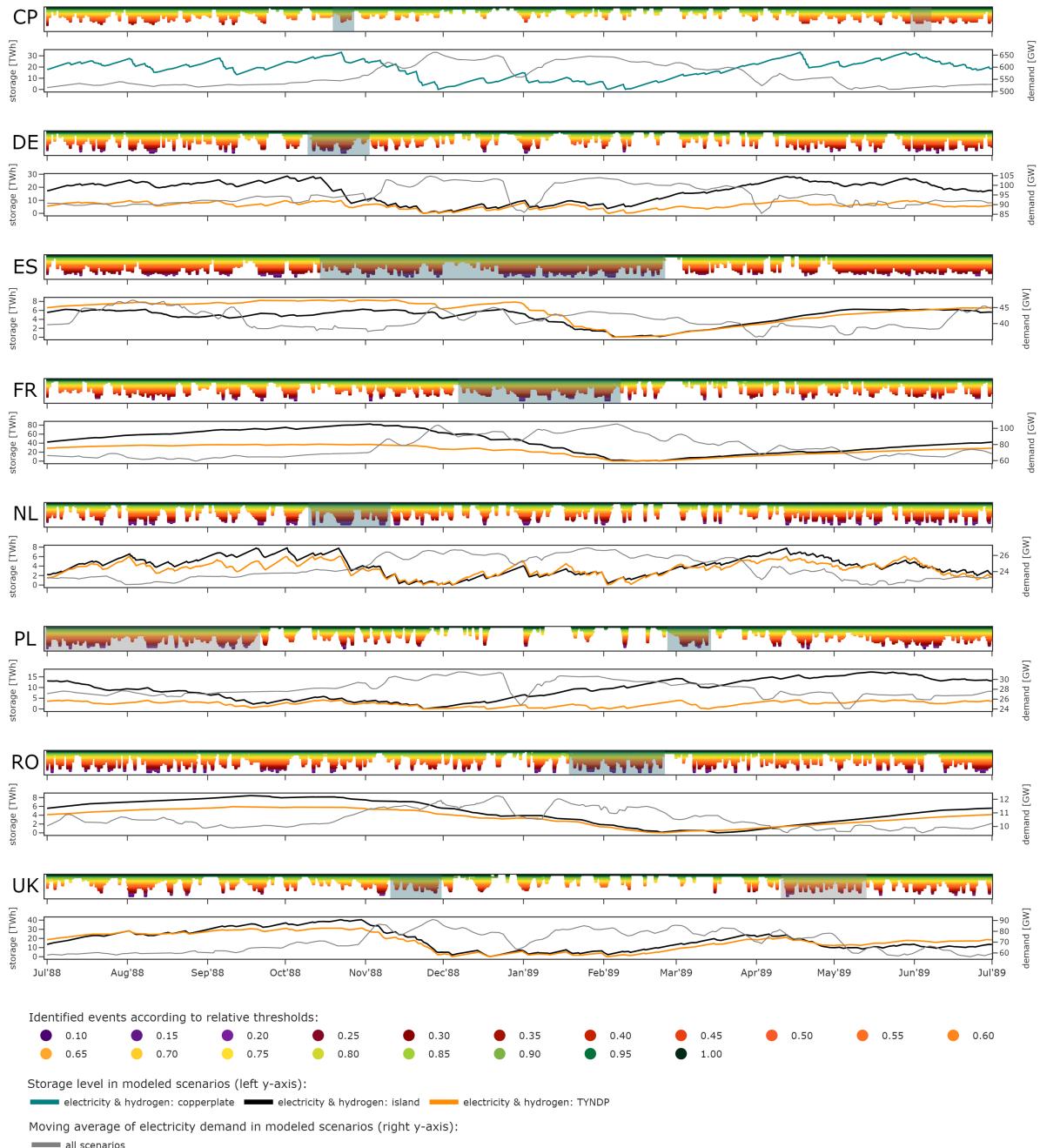
Figure SI.4: Correlation of the drought mass of most extreme winter drought events and normalized storage energy capacity in Germany.

SI.4. Additional discussion of imperfect correlation between extreme drought events and storage size

The scatter plots in Figure 2 indicate that the correlation between the most extreme winter drought event and the optimal long-duration storage size for the same year is not perfect. Several factors explain this. First, country-specific factors such as varying portfolios of variable or firm renewable generation capacity or flexibility options, e.g., high shares of reservoir power plants in the Spanish capacity mix, may cause the imperfect fit. Second, demand peaks vary substantially between weather years in terms of level and temporal variation, especially in winter (compare France in Figure 3). This means that similar droughts can trigger different storage needs, depending on the load situation. Third, our measurement of drought events is, by design, purely based on renewable availability time series and does not consider pre- or succeeding periods of very high availability or the seasonality of electricity demand. In contrast, the power system optimization factors in these aspects. In addition, the drought mass metric based on the VMBT method relies on the choice of a cut-off threshold and is solely an approximation of the cumulative energy deficit of drought events [22], which is relevant for long-duration storage needs. Due to the averaging mechanism of the VMBT method, this metric tends to underestimate solar PV contributions within extreme droughts, particularly in countries with a less pronounced solar seasonality. These contributions generally lead to higher deployment of short-duration system flexibility and lower long-duration storage needs. Finally, VRE portfolios differ to some extent between the drought analysis and the power system model. While these portfolios are fixed in the former, they are optimized in the latter, yielding slightly different capacity mixes between weather years. Yet, the overall fit between the indicators appears to be reasonable, which can also be confirmed by a complementary Germany-only analysis (compare dark and bright lines in Figure SI.4).

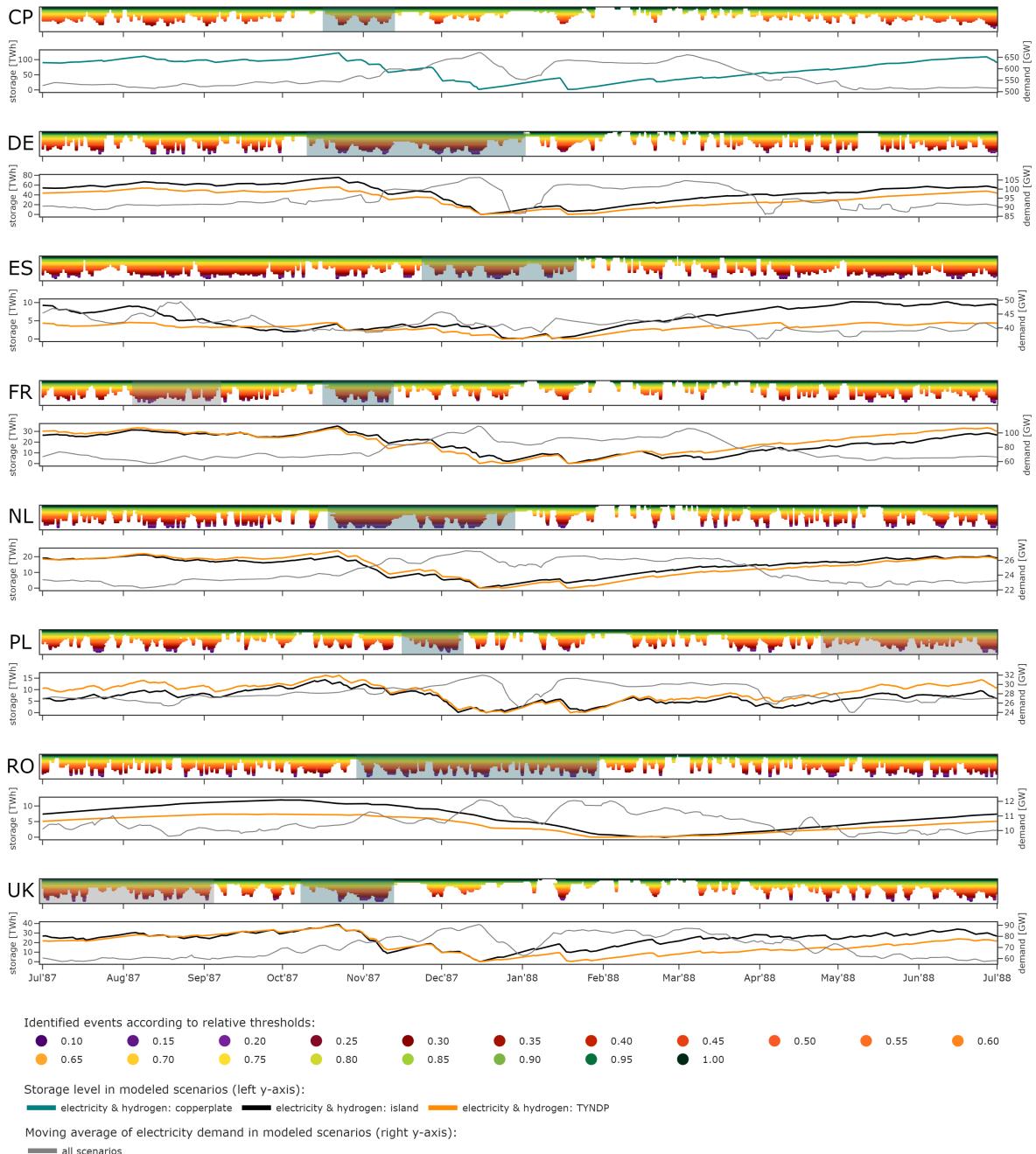
SI.5. Additional illustrations of the impact interconnection on long-duration storage energy

The weather years 1987/88 and 1988/89 exhibit similar long-duration energy storage capacities for the energy island scenario (Figure 4). For increasing interconnection levels, optimal storage capacity diverges, yielding substantially lower energy storage levels for 1988/89 compared to 1987/88. This is because the most pronounced renewable droughts are temporally highly correlated with each other and, to some extent, also with high-demand periods in 1987/88 across many countries. In contrast, this is not the case in 1988/89 (compare boxes in Figures SI.5 and SI.6), enabling more pronounced geographical balancing of these drought events. The temporal overlap is even more pronounced in weather year 1996/97 (Figure 5), which leads to the most extreme pan-European drought in the data (Figure SI.2) and, accordingly, the highest long-duration storage needs (Figure 4).



Notes: For each region, the figure illustrates identified drought patterns lasting longer than 12 hours across all color-coded thresholds (upper panel) and the most extreme drought events occurring in winter (teal boxes). For the UK, where the most extreme drought throughout the year occurs in summer, this event is additionally shown (gray box). The lower panels show exogenous demand profiles, which have been smoothed to highlight demand seasonality. They further display optimized storage state-of-charge levels for isolated countries modeled within the interconnection scenario (1), for policy-oriented interconnection levels in scenario (3), and the pan-European copperplate (CP) in scenario (4).

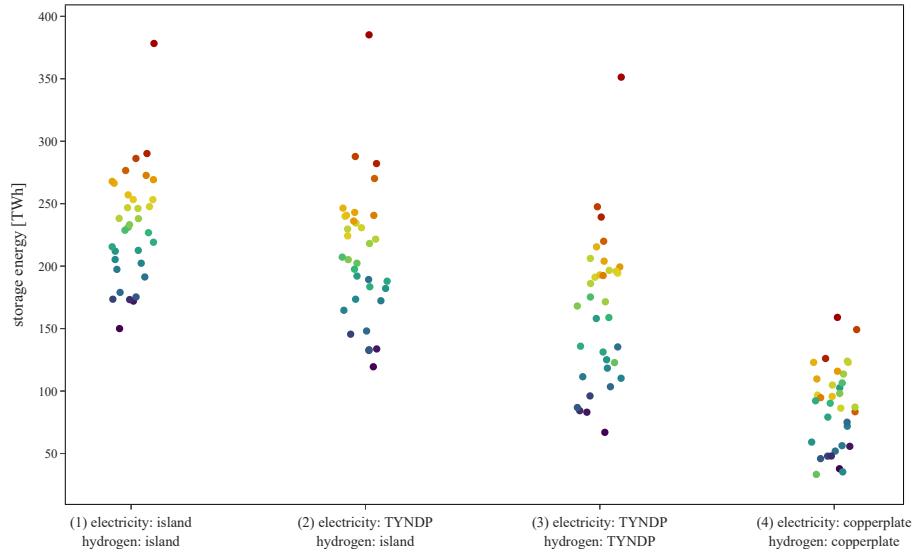
Figure SI.5: Drought events, electricity demand, and state-of-charge of long-duration storage in winter 1988/89 in countries with highest long-duration storage energy capacities.



Notes: For each region, the figure illustrates identified drought patterns lasting longer than 12 hours across all color-coded thresholds (upper panel) and the most extreme drought events occurring in winter (teal boxes). For the UK, where the most extreme drought throughout the year occurs in summer, this event is additionally shown (gray box). The lower panels show exogenous demand profiles, which have been smoothed to highlight demand seasonality. They further display optimized storage state-of-charge levels for isolated countries modeled within the interconnection scenario (1), for policy-oriented interconnection levels in scenario (3), and the pan-European copperplate (CP) in scenario (4).

Figure SI.6: Drought events, electricity demand, and state-of-charge of long-duration storage in winter 1987/88 in countries with highest long-duration storage energy capacities.

Generally, interconnection mitigates long-duration storage energy needs (Figure 4). Overall, the ranking of weather years is relatively persistent, yet the storage-mitigating effect varies between weather years (Figure SI.7), especially for higher levels of interconnection. The mechanisms behind this effect, in particular temporally correlated severe drought events, are illustrated above.



Notes: Every point refers to a single weather year. The coloring changes continuously in long-duration storage energy capacity according to the ranking of weather years in scenario (1). The weather year color remains consistent across the other scenarios.

Figure SI.7: Long-duration storage energy capacity aggregated across all countries for all modeled interconnection scenarios.

SI.6. Additional information on the impact of firm zero-emission generation

Figure 8 indicates a near-linear reduction of long-duration storage capacity for increasing levels of zero-emission generation capacity. Varying ratios of VRE technologies in the capacity mixes explain irregularities in the negative slope. For instance, for a firm zero-emission capacity of more than 43 GW, the model abstains from deploying cost-intensive offshore wind power. Each additional gigawatt of the zero-emission technology has now a significantly higher substitution rate to onshore wind and solar PV compared to scenarios with less capacity. This is because of the difference in full-load hours of these VRE technologies. In Germany, offshore wind has typically around twice the full-load hours of onshore wind and four times as many as PV. In scenarios without offshore wind, additional dispatchable capacity therefore replaces much more onshore wind and PV, which causes a more pronounced decrease in long-duration energy storage capacity.