Coping with the Dunkelflaute: Power System Implications of Variable Renewable Energy Droughts in Europe

Martin Kittel, DIW Berlin, +49 30 89789-536, mkittel@diw.de
Alexander Roth, KU Leuven & DIW Berlin, +493089789-676, alexander.roth@kuleuven.be
Wolf-Peter Schill, DIW Berlin, +49 30 89789-675, wschill@diw.de

Overview

To mitigate climate change and to meet international commitments, the European Union aims to achieve net zero emissions of greenhouse gases by 2050. To achieve this, renewable electricity will play a central role. As wind and solar power offer vast expansion potentials and promise declining costs, they will likely form the backbone of the transition to net zero in most European countries. Yet, with a rising share of such variable renewable energy (VRE), the European power system becomes increasingly exposed to weather variability. 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 (Raynaud et al. 2018; Kittel and Schill 2024).

We combine two open-source tools to investigate how VRE droughts impact the need for long-duration storage in a fully decarbonized European 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.

Methods

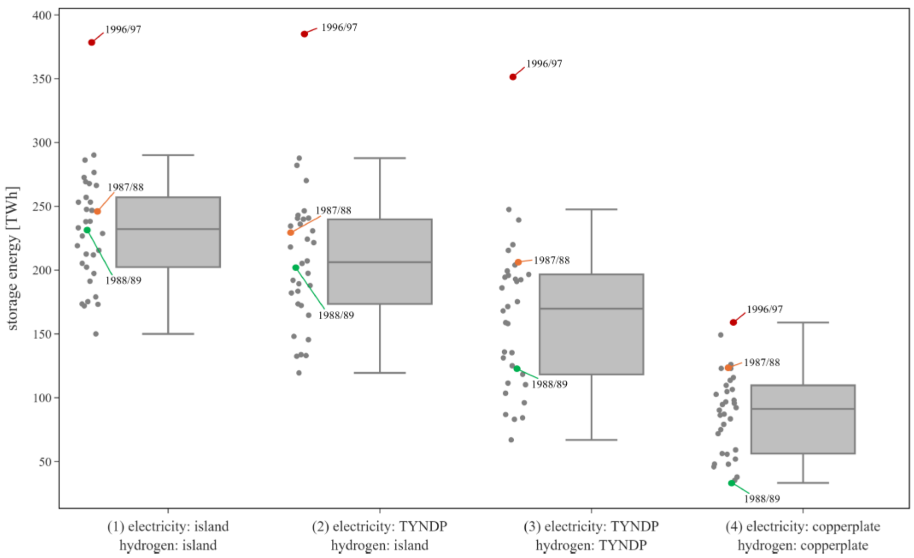
We combine two methods, renewable energy time series analysis and power sector modelling. As for the first, we develop and apply the open-source tool VREDA to identify and evaluate VRE drought patterns based on availability time series. The tool has been designed to implement good practices of multi-threshold drought identification as outlined by Kittel and Schill (2024). In addition, we use the open-source capacity expansion model DIETER (Zerrahn and Schill 2017, Gaete et al. 2021) 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.

We analyze drought patterns and their impact on storage needs for renewable technology portfolios, comprising on- and offshore wind power as well as solar PV, for cases that differ regarding the assumed electricity transmission between countries. This includes completely isolated countries or perfect interconnection across all countries, as well as two cases with more policy-relevant cross-border exchange of electricity and hydrogen. We do so based on 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 PV. Our analysis comprises 33 European countries.

Results

We find that 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.

Interconnection among European countries can significantly reduce the need for long-duration energy storage (Figure). Yet, the storage-mitigating effect of interconnection for dealing with the most pronounced renewable droughts is limited. The storage capacity required for coping with the most extreme events in the data could only be substantially reduced in scenarios with interconnection levels far beyond envisaged grid expansion plans. In contrast, policy-oriented interconnection levels mitigate the storage needs only to a limited extent. Thus, a sizeable need for long-duration electricity storage will remain in a fully renewable European power sector, irrespective of the extent of interconnection. In the most policy-relevant TYNDP interconnection scenario, long-duration storage needs substantially increase to 351 TWh, or more than 7% of yearly European electricity demand.



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.

Sensitivity analyses confirm the robustness of our findings in case moderate levels of firm generation capacity are present. Moderate levels of nuclear power in the capacity mix of five European countries mitigate long-duration storage needs across Europe only to a minimal extent. A 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.

Conclusions

Large-scale adoption of hydrogen-based long-duration storage will likely have long lead times because of supply chain and permitting bottlenecks. 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 storage need of the next highest year 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 further argue that multiple weather years should be used 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.

References

Gaete-Morales, C., Kittel, M., Roth, A., Schill, W.-P. (2021): DIETERpy: a Python framework for The Dispatch and Investment Evaluation Tool with Endogenous Renewables. *SoftwareX* 15, 100784

Raynaud, D., Hingray, B., François, B., Creutin, J. D. (2018): Energy droughts from variable renewable energy sources in European climates. *Renewable Energy* 125. Pp. 578–589.

Kittel, M., Schill, W.-P. (2024): Measuring the Dunkelflaute: How (not) to analyze variable renewable energy shortage. *Environmental Research: Energy* 1, 035007.

Zerrahn, A., Schill, W.-P. (2017): Long-run power storage requirements for high shares of renewables: review and a new model. *Renewable and Sustainable Energy Reviews* 79, 1518-1534.