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Impacts of drought patterns on global and European hydropower plant shortfalls

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Hydropower is a cornerstone of Europe's low-carbon electricity system, yet its reliability is increasingly challenged by intensifying droughts under climate change. Existing assessments of drought risks to hydropower predominantly focus on average water availability or well-studied regions, and rarely quantify how extreme drought duration, frequency and intensity differentially shape plant-level shortfalls worldwide, limiting coordinated adaptation planning.

Here, we compile a global dataset of 28,725 hydropower plants across 165 countries and apply 15 climate–hydrology model combinations under SSP1–2.6, SSP3–7.0 and SSP5–8.5 to identify drought events, characterize extremes in duration, frequency and intensity, and estimate plant-level generation shortfalls while accounting for hydraulic head variations during droughts. We then assess how heterogeneous drought patterns impact hydropower shortfalls across plants, countries and river basins, with a particular focus on Europe.

Under SSP3–7.0 (2030–2060), global annual hydropower losses reach 52–173 TWh yr□¹ (median 114 TWh yr□¹), with generation during drought periods declining by 28% – 49% (median 46%). Europe experiences average losses of 12 - 36 TWh yr□¹ (median 21 TWh yr□¹), corresponding to a 21% - 46% reduction (median 40%) in drought-period output. Across Europe, drought-related shortfalls are most commonly associated with long-duration events, affecting around 74% of installed capacity in major producing countries such as France, Spain, Italy, Norway and Sweden. However, Europe exhibits the highest regional share of frequency-related impacts globally (10%), exceeding the global average, with particularly strong signals in smaller national systems such as Hungary (49%) and Switzerland (13%). High-intensity droughts account for 17% of European capacity, also above the global average, with localized hotspots in eastern and southern Europe, including Moldova (75%), Latvia (57%) and basins in Greece (15%+).

Beyond large stations, we find that small and medium-sized hydropower plants (<100 MW) contribute approximately 56% of total European cumulative losses, rising to nearly 80% under long-duration, low-intensity drought regimes. This highlights a critical source of socio-economic vulnerability, as widespread small-scale facilities underpin regional electricity supply, local livelihoods and energy security.

By resolving drought risks at the plant scale and linking distinct drought patterns to uneven losses across Europe, this study provides an impact-driven evidence base to support targeted adaptation, inclusive resilience planning and decision-making aligned with European climate adaptation objectives.