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Special Section:
Modeling MultiSector Dynamics to Inform Adaptive Pathways

Key Points:
- Extreme weather events doom long-distance power transfers between Laos and Thailand to temporary failures
- Regional droughts increase power production costs and CO_2 emissions by about US$ 120 millions and 2.5 million metric tonnes per year
- The influence of El Niño Southern Oscillation trickles down from summer monsoon to power system behavior

Supporting Information:
- Supporting Information S1

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The Greater Mekong's Climate-Water-Energy Nexus: How ENSO-Triggered Regional Droughts Affect Power Supply and CO_2 Emissions

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Abstract The Greater Mekong Subregion is a transnational area bound together by the Mekong River basin and its immense hydropower resources, historically seen as the backbone of regional economic development. The basin is now punctuated by several dams, successful in attracting both international investors and fierce criticisms for their environmental and societal impacts. Surprisingly, no attention has been paid so far to the actual performance of these infrastructures: is hydropower supply robust with respect to the hydroclimatic variability characterizing Southeast Asia? When water availability is altered, what are the implications for power production costs and CO_2 emissions? To answer these questions, we focus on the Laotian–Thai grid—the first international power-trade infrastructure developed in the region—and use a power system model driven by a spatially distributed hydrological-water management model. Simulation results over a 30-year period show that production costs and carbon footprint are significantly affected by droughts, which reduce hydropower availability and increase reliance on thermoelectric resources. Regional droughts across the Mekong basin are of particular concern, as they reduce the export of cheap hydropower from Laos to Thailand. To put the analysis into a broader climate-water-energy context, we show that the El Niño Southern Oscillation modulates not only the summer monsoon, but also the power system behavior, shaping the relationship between hydroclimatological conditions, power production costs, and CO_2 emissions. Overall, our results and models provide a knowledge basis for informing robust management strategies at the water-energy scale and designing more sustainable power plans in the Greater Mekong Subregion.

Plain Language Summary The development of hydropower dams in the Mekong River basin has historically been seen as a means to support economic growth in Southeast Asia. Because water availability varies on both seasonal and interannual time scales, we hypothesized that an unstable supply of hydroelectricity may temporarily increase reliance on gas and coal, thereby affecting power production costs and carbon footprint. To verify this hypothesis, we developed a coupled water-energy model of the Laotian-Thai grid, the largest power infrastructure in the region. The model represents the relationship between hydroclimatological conditions, water availability, and power system behavior. Simulation results show that prolonged droughts in the Mekong basin reduce hydropower production by about 4,000 GWh/year, increasing the annual production costs and CO_2 emissions by about US$ 120 millions and 2.5 million metric tonnes, respectively. These events are largely explained by the periodic oscillations in the tropical eastern Pacific Ocean that modulate water availability in Southeast Asia. Our findings can help reduce the carbon footprint of power systems and inform the design of hydroelectric dams.

1. Introduction

Power systems provide the fundamental service of balancing electricity supply and demand. Ideally, the service should be reliable, affordable, and sustainable. But, in practice, generating units and transmission networks are often vulnerable to climate-induced disruptions. Changes in water availability, for instance, limit the generation of hydropower dams and steam-cycle thermoelectric plants, leading to higher risks of power shortfall (Turner et al., 2019). Higher ambient temperatures affect peak loads (for space cooling) and reduce the thermal capacity of transmission lines, further stressing the grid (Ke et al., 2016). Disruptions can also cause substantial economic and environmental impacts if temporary losses from renewables must be offset by more expensive and carbon-intensive sources of energy, such as coal or gas. During the 2012–2016 drought in California, for example, utilities faced losses of about US$ 2.0 billions, while CO_2 emissions increased by 10% compared to predrought conditions (Gleick, 2015; Kern et al., 2020). Other recent examples can be drawn from Brazil (Prado et al., 2016) or Europe (De Felice et al., 2020). To design more sustainable grid operations, we need to quantify, understand, and explain the relationship, or nexus, between climate, water, and energy.

Process-based hydrologic models are the most common tool for studying the relationship between water availability and electricity generation. Since the dimensions of the relationship are multiple, different aspects have been explored, including generation types—hydroelectric and thermoelectric, taken individually or together (Liu et al., 2016; Wang et al., 2019)—spatial domains—national, regional, and global (Liu et al., 2017; Stillwell & Webber, 2013; van Vliet et al., 2016)—and timeframes—from seasonal to long-term (Ng et al., 2017; Turner, Ng, & Galelli, 2017). The majority of impact metrics revolve around the effect of water availability on power supply, with a few works considering cross-sectoral impacts, such as electricity prices (van Vliet et al., 2013) or investment needs (Turner, Hejazi, et al., 2017). Something that all these studies have in common is a boundary drawn at the interconnection between water and power systems. And yet, it is only by placing dams and thermoelectric plants in a broader water-energy context that we can fully understand how water availability affects power systems behavior, especially during heat waves and droughts (Voisin et al., 2018). From a modeling perspective, this means coupling hydrologic models with power system models representing the broad spectrum of decisions made at the grid scale—for example, commitment of generating units, electricity generation and transmission. Multimodel multiscale frameworks represent the nuances in the links between water and energy systems, thereby offering a tool for explaining how hydroclimatic extremes affect power systems operations (Su, Kern, Reed, & Characklis, 2020; Turner et al., 2019; Voisin et al., 2016).

Notwithstanding these recent advances, a deeper understanding of the climate-water-energy nexus is needed to support management and planning interventions at the grid scale. A first complexity is the relation between power system performance and the differential impact of climate across multiple basins within a region. Knowledge about such relation is particularly important for systems that rely on long-distance, international interconnections—examples are many, ranging from the Southern African Power Pool to the ASEAN Power Grid (Ahmed et al., 2017; Wu et al., 2017). Interconnections are meant to transfer electricity from unevenly distributed production sites to load centers, but may accidentally expose them to unforeseen risks—for example, by connecting them to temporarily water-scarce areas. Second, we need to understand whether the signature of large-scale climate features, such as the El Niño Southern Oscillation (ENSO), is detected concurrently on both water and power systems. ENSO, for instance, affects temperature, rainfall, and hydropower supply in several regions (Chiew & McMahon, 2002; Ng et al., 2017), so one would expect ENSO-driven droughts to modify the energy generation mix or increase the risks of power shortfalls. With the only exception of Voisin et al. (2018), this hypothesis has not been tested. Since *teleconnections* represent one of the physical mechanisms upon which seasonal hydrometeorological forecasts are issued, verifying the hypothesis would allow us to predict grid operations and design contingency measures. Finally, the existing literature on coupled water-power system models is biased toward developed countries (Byers et al., 2020; Kern & Characklis, 2017; O'Connell et al., 2019; Su et al., 2017), and thus overlooks large regions where electricity infrastructures have, and will, experience a tumultuous growth (Shearer et al., 2017; Wang et al., 2019; Zarfl et al., 2015)—possibly exacerbating the conflict with other water users (Satoh et al., 2017). How these fast-growing systems respond to hydroclimatic variability remains an open question.

Here, we focus on the Greater Mekong Subregion, a transnational area bound together by the Mekong River, whose immense hydropower potential has historically been seen as a means to support economic growth and cooperation between countries (Yu, 2003). While China and Vietnam are using the available portions of the Mekong—the Lancang and part of the 3S basins (Sekong, Sesan, and Sre Pok), respectively—for local hydropower supply, Thailand and Laos have developed the first large-scale, cross-border, power-trade infrastructure (Watcharejyothin & Shrestha, 2009). Through this interconnection, Thailand imports almost 90% of Laos' electricity production, which depends heavily on hydropower dams in the Mekong. The Chao Phraya River basin is a second fundamental element of the Laotian-Thai water-energy system, as it provides water for both hydropower and thermoelectric plants. The electricity demand is almost constant throughout the year, while water availability follows a monsoon-like pattern, with prolonged dry spells in the period from November to April. Importantly, water availability in both rivers varies on an interannual timescale as well, in response to changes in the sea surface temperature over the tropical Pacific Ocean (Räsänen et al., 2016; Singhrattna et al., 2005). These pronounced changes in water availability—and their association with features of variability of the earth-atmosphere system—raise the prospect of a tight relation between hydroclimatic variability and energy generation mix. Prolonged shortfalls of hydropower production, for example, may be offset by increased electricity production from gas and coal, with a consequent increase of production costs and CO_2 emissions. The questions of interest are therefore the following: How do teleconnections between large-scale climate drivers and local hydrometeorological processes affect the energy generation mix? When water availability is altered, what are the implications for power production costs and CO_2 emissions? Is the behavior of the power system sensitive to the spatial footprint of droughts across the Mekong and Chao Phraya?

To answer these questions, we adopt a multimodel multiscale approach hinged on the coupling between two spatially distributed models. The hydrologic-hydraulic model simulates the relationship between hydrometeorological forcings and water availability in the Mekong and Chao Phraya basins, while the power system model reproduces the operating decisions made in the Laotian-Thai grid (Section 2). By accounting explicitly for the constraints imposed by water availability on hydro and thermoelectric plants, the coupled models help us untangle the relationship between climate, water, and energy variables (Section 3). Building on this knowledge, we identify opportunities for the join management of water and energy resources and discuss plans for future capacity expansions (Sections 4 and 5).

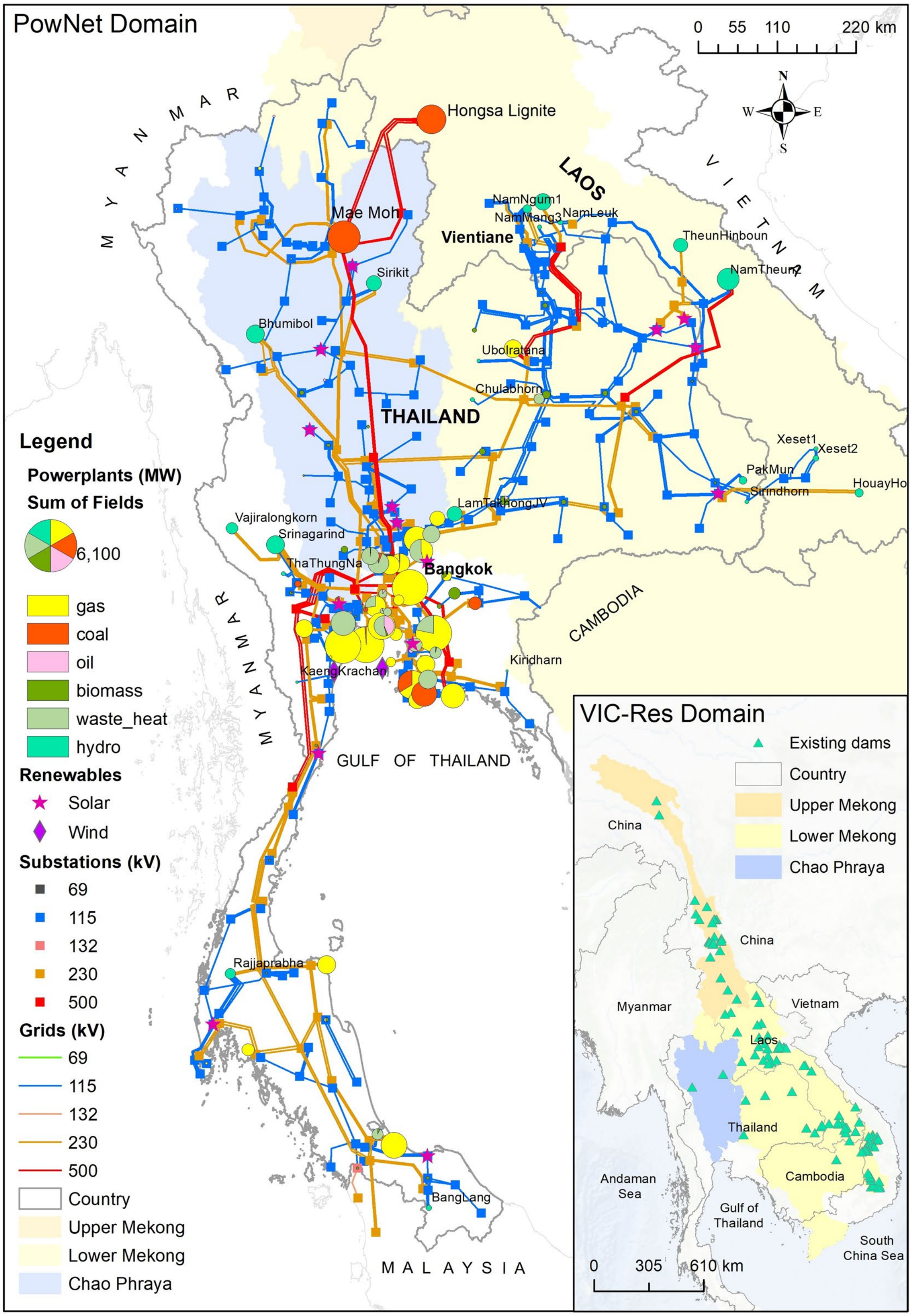
2. Materials and Methods

2.1. The Laotian-Thai Water-Energy System

Figure 1 shows the main infrastructure of the Laotian-Thai water-energy system operated in 2016, the most recent year with comprehensive and reliable data (EPPO, 2017). The plants located in Thailand have a total installed capacity of 42,531 MW, with the Laotian ones contributing an additional 5,362 MW. The annual system-wide generation of ~198,100 GWh relies, in order of importance, on gas-fired power plants (63.2% of the annual generation), coal (18.6%), biomass and waste heat (6.2%), hydropower (1.8%), oil, wind, and solar (below 1%) (EGAT, 2016; IRENA, 2017). The remaining 10% of electricity supply is provided by the Laotian plants. Specifically, Thailand imports almost the entire generation of nine hydropower dams (total installed capacity of 3,485 MW) and one coal power plant (Hongsa Lignite; 1,878 MW). This import is regulated by a long-term power purchase agreement between the Electricity Generating Authority of Thailand (EGAT) and Électricité Du Laos (EDL) (EDL, 2016; EGAT, 2016). To put the extent of this agreement into perspective, consider that Thailand has direct access to 5,362 of the 6,688 MW of capacity installed in Laos. In recent years, minor steps have been taken to create a liberalized electricity market, but the supplier side is still de facto controlled by EGAT, who benefits of a monopoly position (Dubash & Williams, 2017).

The Mekong and Chao Phraya river basins are two fundamental components of the water-energy system. Naturally, hydropower production depends on water availability: all Laotian dams exporting to Thailand are located in the Mekong basin; of the 14 Thai dams, five are in the Mekong, two in the Chao Phraya (Bhumibol and Sirikit; total installed capacity of 1,279 MW), and seven in smaller basins. Additional details about all hydropower dams are provided in Table S1. Some thermoelectric plants depend on freshwater availability (see Table S2). The Mekong provides cooling water for Hongsa Lignite coal power plant (HPCL, 2018), as well as a few smaller plants located in Thailand. The Chao Phraya supports the operation of five thermoelectric plants, including Mae Moh plant (2,400 MW capacity). The remaining plants, strategically located near Bangkok metropolitan area and its gas import facilities (DBS, 2017), do not depend on freshwater supply.

A comparison between total installed capacity and system-wide peak hourly demand (29,892 MW, EGAT (2016)) indicates that the power system should be able to maintain a reserve capacity of about 30%, well-above the minimum requirement of 15% (EGAT, 2016)—this is a trait shared by other power systems in Southeast Asia, where shortfalls of electricity supply are often caused by the poor state of distribution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networks rather than limited reserve capacity (ADB, 2012). Instead, its generation mix, carbon footprint, and production costs may largely depend on the state of the Mekong and Chao Phraya river basins. There are three aspects worth considering here. First, most of the annual rainfall is delivered by the Southwest Monsoon (roughly, from May to October), so streamflow shows a pronounced seasonal pattern. Second, ENSO modulates the summer monsoon on an interannual time scale. Warm conditions in the tropical Pacific (El Niño) delay the monsoon onset and shorten the overall rain season, while cold conditions (La Niña) are associated to wetter conditions in mainland Southeast Asia (Cook & Buckley, 2009; Singhrattna et al., 2005). Third, streamflow in the Mekong and Chao Phraya river basins is spatially coherent, owing to common meteorological and climatological drivers (Nguyen et al., 2020). We thus expect water availability and dispatchable hydropower to show seasonal and interannual modes of variability in both basins.

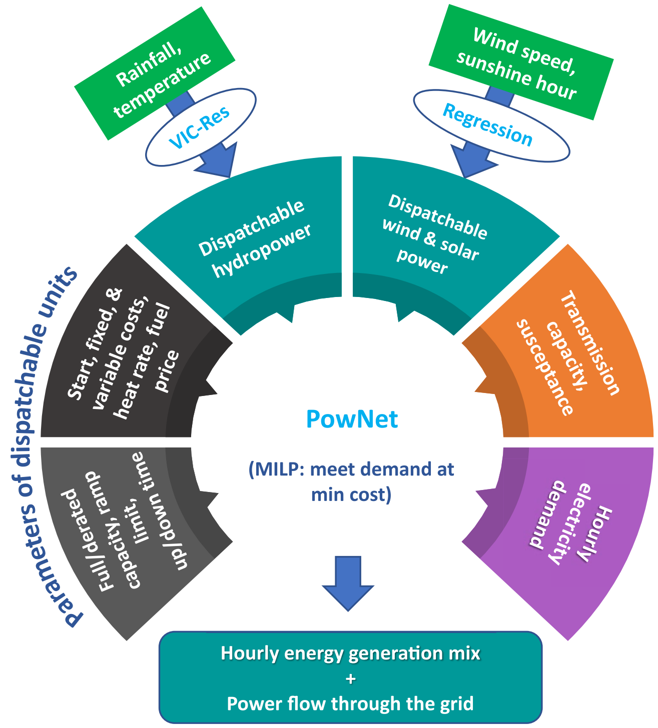

Figure 2. Graphical representation of PowNet's input-output data. The term MILP refers to the Mixed-Integer Linear Program solved by PowNet.

2.2. Power System Simulation

The dynamic behavior of the Laotian-Thai power grid is simulated with PowNet (Chowdhury, Kern, et al., 2020). Similarly to other production cost models (e.g., PROMOD (ABB, 2020), PyPSA (Brown et al., 2018), CAPOW (Su, Kern, Denaro, et al., 2020)), PowNet simulates the decision-making problem of determining (1) which generating units to start-up and shutdown (Unit Commitment) and (2) the amount of power supplied by each unit (Economic Dispatch). Importantly, PowNet simulates the power flow through the grid, thereby explicitly representing the high-voltage transmission lines. This is a fundamental, yet often overlooked, aspect of rapidly evolving power systems, where the deployment of new generation facilities—particularly variable renewable resources—can lead to transmission congestion (Chowdhury, Dang, et al., 2020; Sharpe, 2019;). From a mathematical modeling perspective, the model solves a network-constrained Mixed-Integer Linear Program that minimizes the production costs while meeting the electricity demand at all substations. PowNet works with an hourly time step and a planning horizon of 24 h.

Since the electricity supply is controlled by a single authority, the total power production costs (in US$) are well estimated by accounting for the use of thermoelectric generating units and amount of electricity imported from Laos. The relative production costs of the Thai variable renewable resources (i.e., hydro, solar, and wind) are considerably smaller, and hence negligible for the Unit Commitment/Economic Dispatch process (Kern & Characklis, 2017). As illustrated in Figure 2, the scheduling and dispatch of hourly electricity depends on several other factors, including the design features of the thermoelectric plants, derated capacity of individual plants, amount of power available from the variable renewable resources, minimum requirements of reserves, capacity and susceptance of the transmission lines, and transmission losses.

PowNet is implemented to mimic the 2016 configuration of the Laotian-Thai power grid. The design features of the dispatchable units are collected from technical reports (EGAT, 2016; EPPO, 2017), while the technoeconomic parameters are gathered from either global databases (EPA, 2015; EIA, 2016) or previous studies (Kern & Characklis, 2017); see Table S3 for additional details. Load shedding is modeled by add-

Figure 1. Main components of the Laotian-Thai water-energy system. The areas shaded in blue, yellow, and orange denote the Chao Phraya, Lower Mekong, and Upper Mekong basins, while circles, squares, and segments indicate power plants (thermoelectric, biomass, and hydropower), substations, and high-voltage transmission lines. Solar and wind plants are illustrated with stars and diamonds. Note that the size-proportionate scaling is applied only to thermoelectric, biomass, and hydropower plants, which have comparable capacities. The pie charts illustrate cases in which more than one generator is connected to a substation. All components of the power grid were operational in 2016. In the inset, we report the full spatial extent of the Chao Phraya and Mekong basins, together with the dams operated by all riparian countries. These dams are modeled by the hydrologic-hydraulic model VIC-Res.VIC, Variable Infiltration Capacity.

ing hypothetical "slack" generators (with high capacity and cost, but low ramping time) to some nodes with high demand. As for the high-voltage transmission lines, we used data on length, size, number of circuits, and voltage level (EPPO, 2015; EPPO, 2018) to estimate their capacity and susceptance. The minimum hourly reserve is set to 15% of the system-wide demand (cfr. Guerra et al., 2016), while generation is discounted by 7.5% to account for the transmission losses (EGAT, 2016). 25% of the transmission lines' capacity is kept unused as safety margin (cfr. Schlecht & Weigt, 2014). The hourly electricity demand at each substation is estimated starting from province-wise, monthly varied peak electricity demand, collected from EPPO (2017). Both spatial and temporal disaggregation rely on a common approach in power system modeling (see Chowdhury, Kern, et al., 2020, and references therein). The former depends on the voltage level of the substations, the latter is based on weekday-weekend and peak-off-peak demand profiles to account for the variation among days in a week and hours in a day. We note that the electricity demand data implicitly capture the sensitivity of demand to air temperature, a potent driver of air conditioning need, which slightly increases in premonsoon months—when the air temperature increases by 2–3 degree Celsius with respect to the annual average (Figure S1).

The amount of power available from the variable renewable resources is modeled separately. The production of wind and solar farms is modeled with a regression model, using wind-speed and sunshine-hour data (as in Papavasiliou et al. (2015) and Blair et al. (2014)), collected from the Thai Meteorological Department's website (TMD, 2020). The hourly availability of hydroelectricity is simulated with the hydrologic-hydraulic model VIC-Res, as explained in the next section. VIC-Res is also used to estimate the amount of water available at the freshwater-dependent thermoelectric plants, an information needed to calculate the adjustment factor of their usable capacity during the driest periods. Ideally, the calculation of the adjustment factor should be based on both water availability and observations of used water for cooling, but the latter information is not available for the study site—a common difficulty when modeling power systems. We therefore rely on a simpler approach, often adopted in similar modeling contexts (see O'Connell et al., 2019, and references therein), where the adjustment factor depends on a comparison between annual and long-term (annual average) water availability in the stream closest to each plant. For years in which water availability is lower than the long-term one, we define the adjustment factor as the ratio between annual and long-term water availability and apply such ratio only to the premonsoon months, thereby assuming that plants can operate at full capacity during the rest of the year—recall that most of the rainfall is delivered during the Southwest Monsoon, even during dry years. Our estimates of derated capacity, or loss of usable capacity, are in line with those reported by Wang et al. (2019) for Thailand (see Table S2 and Figure S6 for further details). With this set-up, PowNet is validated against 2016 data on generation mix, production costs, and CO_2 emissions (see section S1).

2.3. Water Availability Simulation

To capture the relationship between hydrometeorological processes and water availability over large domains, such as the Chao Phraya and Mekong basins, it is best to adopt a spatially distributed, hydrologic-hydraulic model. Here, we rely on VIC-Res (Dang, Vu, et al., 2020), a variant of the flow routing model commonly used as a postprocessor with the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al., 1994; Lohmann et al., 1996, 1998). Both VIC and VIC-Res proceed by first organizing the spatial domain into a number of computational cells, where baseflow, runoff, infiltration, and evapotranspiration are estimated as a function of various hydrometeorological forcings. The simulated runoff is then routed through the river network. In VIC-Res, the river routing process includes an explicit representation of storage and release dynamics of all reservoirs. This is achieved by determining the dam locations, implementing a number of cells in which the storage dynamics are calculated, and adopting bespoke rule curves that determine the release as a function of water level and dam design specifications. Using the information on release through turbines and hydraulic head, VIC-Res finally calculates the hydropower available at each dam. The explicit representation of the operating rules yields two advantages with respect to more traditional approaches that estimate available hydropower based on the postprocessing of simulated discharge. First, VIC-Res accounts for the cascading effect of hydropower operations—a feature particularly important in the Lower Mekong, whose flows are affected by dams located in upper reaches of the basin (Hecht et al., 2019). Second, we ensure that both model parameterization and representation of key hydrological processes are not flawed by the misrepresentation of dam operations (Dang, Chowdhury, et al., 2020).

As shown in Figure 1 (inset), water and hydropower availability are simulated over a large spatial domain comprising both Mekong and Chao Phraya River basins. For the Mekong, we consider a domain of ∼635,000 km^2 ranging from the upper reaches of the Lancang to the station of Kratie (Cambodia). In this domain, we represent the operations of 108 dams operational in 2016 (across China, Laos, Thailand, Cambodia, and Vietnam), including the 14 dams feeding the Laotian-Thai power system (see section 2.1). For the Chao Phraya, we model an area of ∼110,000 km^2, which is partially controlled by Bhumibol and Sirikit dams. To keep the model implementation consistent across the two basins, we adopted the same setup and input data: the spatial resolution is 1/16th of a degree, with which we accurately represent the location of each dam, while rainfall and temperature data are retrieved from APHRODITE (Yatagai et al., 2012) and CFSR (Saha et al., 2014), which were found to be reliable for the region of interest (Lauri et al., 2014). As for the hydropower reservoirs, we gathered data on dam design specifications and operating rules from the Mekong River Commission, the International Commission On Large Dams, and the Global Reservoir and Dam Database. Further details on the representation of reservoirs in VIC-Res are provided in Section S2.1, while the calibration and validation results are reported in Section S2.2. For the handful of dams and freshwater-dependent thermoelectric stations falling outside the Mekong and Chao Phraya basins, we resorted to a simpler representation of the hydrological processes (Section S3).

2.4. Experimental Setup and Analysis

Since our goal is to understand how water availability affects power system performance, we proceeded by isolating changes in the infrastructure while emphasizing the effect of hydroclimatic variability; a common choice in power system modeling (e.g., De Felice et al., 2020; Pereira-Cardenal et al., 2014; Voisin et al., 2016). We achieved this by keeping the setup on power plants, transmission facilities, and power demand for the year 2016 and forcing VIC-Res with 30 years of precipitation and temperature data spanning the period 1976–2005. In other words, we evaluate the exposure of the current grid configuration to hydroclimatic conditions observed in the recent past. There are two reasons behind the choice of the period 1976–2005. First, the teleconnection between ENSO and the summer monsoon in continental Southeast Asia started to strengthen in the 1970s (Singhrattna et al., 2005). Second, the period includes two particularly strong El Niño events, observed in 1982–1983 and 1997–1998 (Capotondi & Sardeshmukh, 2017).

To characterize the behavior of the water-energy system, we consider a few explicatory variables for each subsystem. For the Mekong and Chao Phraya, we use the Streamflow Drought Index (SDI), an indicator of drought intensity found effective for river basins characterized by significant storage works (Nalbantis & Tsakiris, 2009). The SDI is calculated through the following steps. First, we estimate the monthly streamflow volume from the daily discharge data simulated at hydropower and freshwater-dependent thermoelectric plants. We then apply a Box-Cox transformation and standardization, and finally spatially aggregate the data to produce one index for each basin. The magnitude of the SDI quantifies the intensity of a given event, while negative and positive values correspond to droughts and pluvials. For power supply, we analyze the available hydropower (calculated by VIC-Res), the unavailable capacity of freshwater-dependant thermoelectric plants, the electricity generation mix, production costs, and CO_2 emissions. (Reliability metrics, such as the reserve margin, are reported only in the Supplement, since grid reliability is not an issue.) All variables are aggregated at monthly and annual time steps—for the latter, we use the calendar year, instead of the hydrological year, following a standard practice in energy statistics.

To test the hypothesis that grid operations are sensitive to ENSO, we classify each year in the study period as either El Niño, Neutral, or La Niña. We adopt the classification provided by the Japan Meteorological Agency (https://www.coaps.fsu.edu/jma), but tailor it to our study site by shifting the years back by one, so as to account for the time that ENSO takes to affect Southeast Asia—for example, we classify 1998, instead of 1997, as an El Niño year. In our 30-years data set, we isolate seven El Niño and four La Niña years, with the remainder classified as Neutral (Table S4). The resulting classification is used in a composite analysis with which we explore how the water-energy variables vary during the ENSO phases.

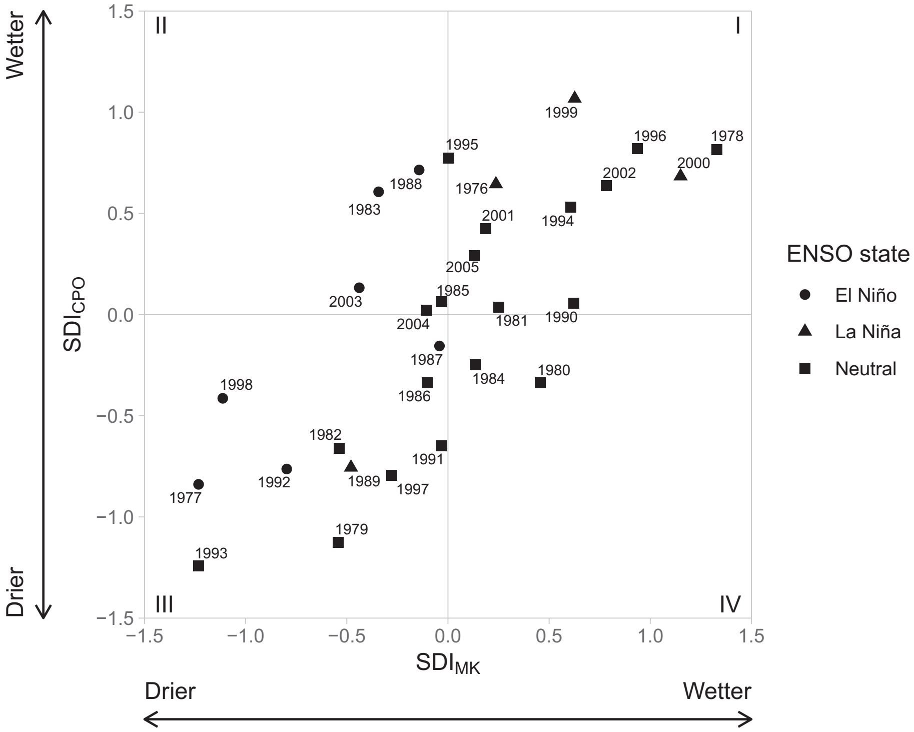

Figure 3. Scatter plot illustrating the relationship between local hydrological processes and El Niño Southern Oscillation (ENSO). The horizontal and vertical axes correspond to the Streamflow Drought Index of the Mekong and Chao Phraya (SDI_{MK} and SDI_{CPO}), while the ENSO state is represented with three symbols, indicating El Niño (circle), Neutral (square), and La Niña (triangle) conditions. Roman numerals denote the four different panels.

3. Results

This section moves along three phases. First, we quantify the exposure of hydropower and thermoelectric plants (built and operated in 2016) to past climate variability. Then, we use this information to understand how generation mix, production costs, and carbon dioxide emissions vary in response to droughts, pluvials, and ENSO phases. Finally, we carry out a probabilistic assessment aimed at determining the likelihood of the most extreme events.

3.1. Impact of Hydroclimatic Variability on Hydropower and Thermoelectric Plants Availability

Before introducing the impact of droughts on the availability of hydropower, coal-fired, biomass, and waste heat plants, we characterize the hydroclimatological context observed during the period 1976–2005. Specifically, we analyze the annual values of the SDI in the Mekong and Chao Phraya (SDI_{MK} and SDI_{CPO}), reported on the horizontal and vertical axes of Figure 3, and relate them to the state of ENSO. The first, fundamental, pattern to notice is that both basins exhibit a similar behavior over time, meaning that the majority of pluvials and droughts are synchronized (first and third quadrants). The depth, or intensity, of these events is comparable across the two basins, as shown by the SDI range of variability. A second pattern is the response to ENSO. All El Niño events are associated to dry conditions in either or both basins; La Niña events tend to increase water availability throughout the spatial domain. A notable exception is the 1989 La Niña, when positive rainfall anomalies were limited to central Vietnam, leaving the Mekong and Chao Phraya basins drier than average (Räsänen et al., 2016).

The impact of hydroclimatic variability on the hydropower budget is profound: as shown by the color bar of Figure 4a, the anomalies of available hydropower vary between ±4,000 GWh. This range is equivalent to about one-third of the annual hydropower availability, indicating that dams have limited capability to smoothen interannual inflow variability. Since most of the hydropower potential is realized by dams

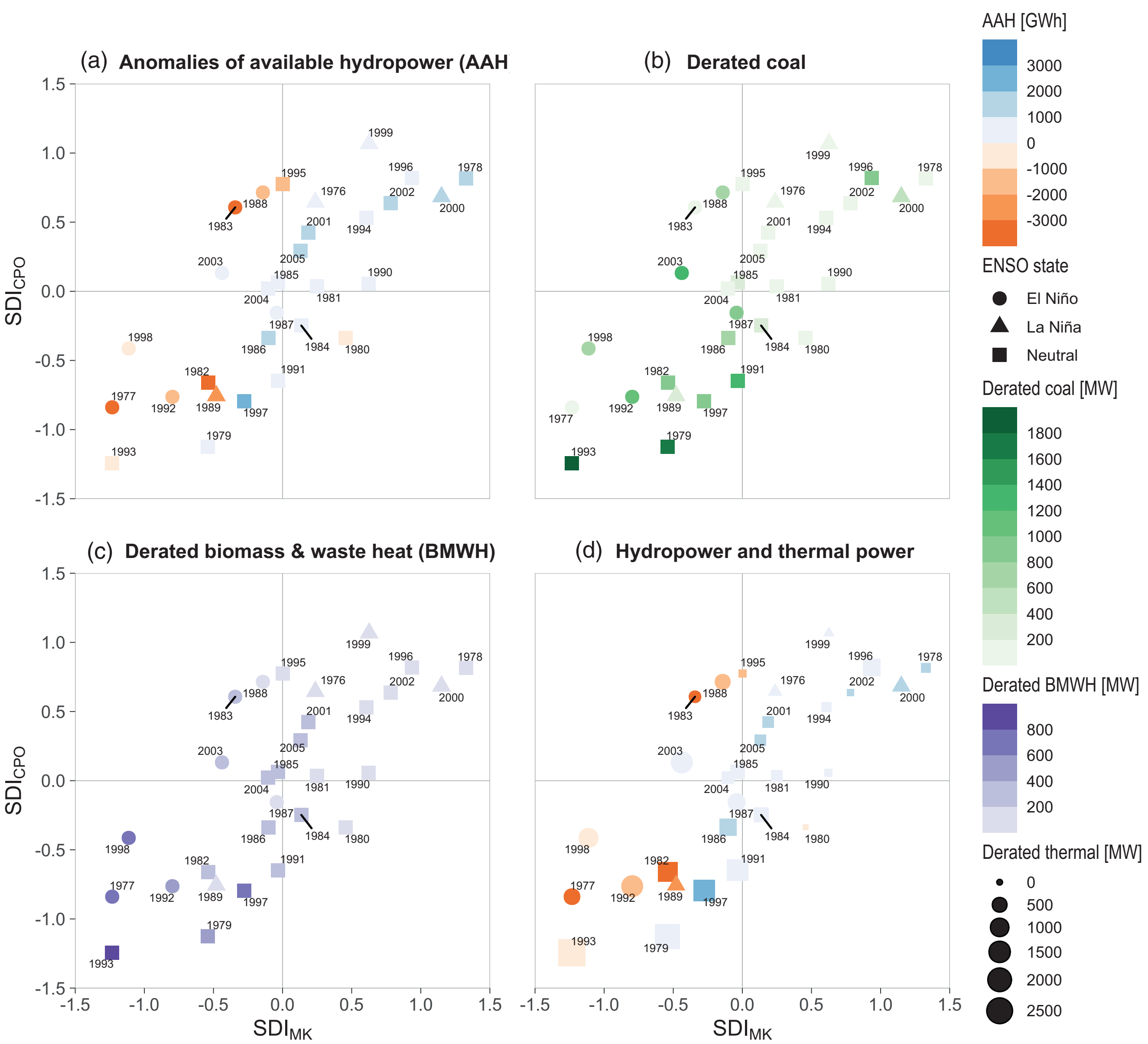

Figure 4. Scatter plots illustrating the impact of hydroclimatic variability on hydropower plants (a), coal-fired plants (b), and biomass and waste heat plants (BMWH) (c). (Note that in panel (c) we included the only freshwater-dependent gas-fired plant.) For hydropower, we calculate the annual anomalies of available hydropower, while for the freshwater-dependent thermoelectric plants we calculate, on annual basis, the derated capacity. In each scatter plot, the horizontal and vertical axes correspond to the Streamflow Drought Index of the Mekong and Chao Phraya (SDI_{MK} and SDI_{CPO}), while points correspond to the annual values of the aforementioned variables. The ENSO state is represented with three symbols, indicating El Niño (circle), Neutral (square), and La Niña (triangle) conditions. In panel (d), we aggregate the impact of hydroclimatic variability on all plants: anomalies of hydropower budgets are represented by colors, while the derated capacity of thermoelectric plants is represented by the size of the symbols.

in the Mekong, droughts affecting this basin (second and third quadrants) have a bigger impact on hydropower availability than droughts affecting the Chao Phraya alone (fourth quadrant). As we shall see later, the unavailability of cheap hydropower from Laos limits the effectiveness of long-distance power transfers to Thailand, with a consequent impact on the overall generation mix and associated production costs. Another important point revealed by Figure 4a is that more intense droughts do not necessarily lead to larger anomalies of hydropower availability; see, for example, the years 1977 and 1983, which present similar anomalies (about −4,000 GWh) but different drought intensities. This result is explained by the drought spatial patterns: as shown in Figure 5, different patterns can result in similar effects if the

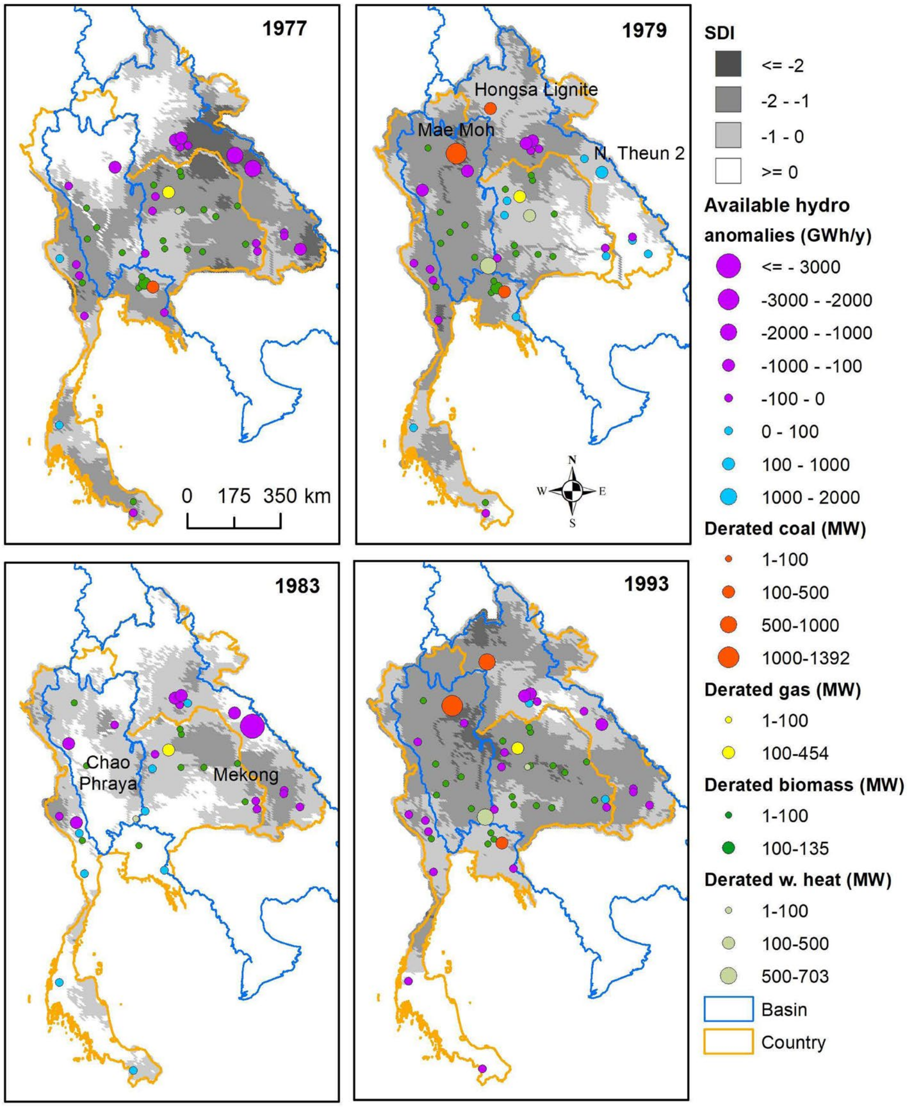

Figure 5. Spatial distribution of the SDI for four selected years. The impact of hydroclimatic variability on the power system is quantified with the same variables used in Figure 4: annual anomalies of available hydropower (in GWh) and derated capacity of freshwater-dependent thermoelectric plants (in MW). Note that the capacity of the two main coal-fired plants (Mae Moh and Hongsa Lignite) is derated only in 1979 and 1993. SDI, Streamflow Drought Index.

main impacted units (Nam Theun two and Nam Ngum 2, in this case) are exposed to events of comparable depth. (The reader is referred to Figure S5 for an additional analysis of drought spatial patterns and impacted units.)

The exposure of freshwater-dependent thermoelectric plants to hydroclimatic variability is quantified by calculating the total annual unavailable, or derated, capacity. Beginning with coal (Figure 4b), we find that the largest value of derated capacity is ~1,500 MW in Thailand and ~750 MW in Laos (Table S2 and Figure S6), corresponding to about 27% and 40% of the installed capacity. Since coal-fired plants are located in both Mekong and Chao Phraya basins (Section 2.1), the most impactful droughts are the ones affecting both basins concurrently. Similarly to the case of hydropower, the overall impact of droughts depends not only on severity, but also on geographical extent. This concept is exemplified by the 1979 and 1993 events, whose spatial patterns are illustrated in Figure 5. Similar conclusions can be drawn for the biomass and waste heat (BMWH) plants (Figure 4c), whose role in the Laotian-Thai water-energy system is more marginal.

We consolidate the results from the previous steps in Figure 4d, where colors represent the annual anomalies of hydropower budget and size represents the unavailable capacity of thermoelectric plants (aggregated across coal, biomass, and waste heat plants). The plot reveals the overall exposure of the Laotian-Thai water-energy system to hydroclimatic variability. When both basins are in normal or wet conditions (positive values of SDI), we observe large, positive, anomalies of hydropower availability. When the Mekong, or both basins, are in dry conditions, we find events affecting the hydropower dams (e.g., 1977, 1983), thermoelectric plants (e.g., 1979, 1993), and a combination thereof (e.g., 1982, 1992). As explained above, the reason behind these "different droughts" has to be sought in the position of impacted units—a critical factor in determining the system's exposure. Considering the relationship between SDI and ENSO state—as well as the limited buffer effect of hydropower dams—it is therefore not surprising to note that many anomalies of power availability happen in concomitance with El Niño-like conditions.

3.2. Cumulative Impact of Water Availability on Generation Mix, Production Costs, and CO_2 Emissions

How does the exposure of hydropower and thermoelectric plants to hydroclimatic variability affect the power system's performance? To answer this question, we study the annual anomalies of hydropower, coal, gas, and biomass supply, productions costs, and CO_2 emissions—all simulated by PowNet, using the cost parameters and CO_2 emissions factors reported in Section S1. These variables are illustrated in Figure 6, together with the hydroclimatological conditions characterizing the study period. The figure highlights the fundamental role played by the Mekong's dams: when their production drops (Figure 6a, second and third quadrants), the power system responds by increasing its reliance on thermoelectric plants (Figures 6b–6d). In turn, this largely affects production costs and CO_2 emissions. "Hydropower droughts"—like those experienced in 1977 or 1983—increase production costs and emissions by more than 100 M$ and 2 Mt per year, respectively. Pluvials have the opposite effect: by increasing water availability and hydropower supply, they dwindle the carbon footprint. Overall, we find that hydroclimatic variability alone makes annual production costs and CO_2 emissions vary in a range of about 250 M$ and 5 Mt. The signature of ENSO is clear: during El Niño years, costs and emissions increase, on average, by 50 M$ and 1 Mt (Figure S7). In other words, the teleconnection between Pacific Ocean sea surface temperatures and the Mekong's hydrological processes permeates through the power grid, influencing the operations of the thermoelectric sector and its carbon footprint.

To better understand the role played by thermoelectric stations, we visualize the annual values of ten water-energy variables in a parallel-coordinate plot (Figure 7). The variables are shown in 10 parallel axes, so each line connecting the axes represents a different year. The figure illustrates three important behaviors. First, coal, gas, biomass, and waste heat plants are never used at full capacity, even when the Mekong's dams hit the lowest production levels—note the diagonal lines crossing the axes $\mathrm{Coal}_{\mathrm{LA}}$, $\mathrm{Coal}_{\mathrm{TH}}$, Gas, and BMWH. This behavior is explained by the large reserve capacity (see Figure S8). Second, coal-fired (in Thailand), biomass, and waste heat plants tend to be the preferred options, because they are the cheapest alternative. Yet, when their capacity is affected (as in 1979 or 1993), gas plants are run at higher capacity. When this happens, production costs and CO_2 emissions are decoupled, with the former increasing and the latter reaching the lowest levels. In other words, there can be instances in which droughts lead to a decrease of CO_2 emissions. Third, there is a dichotomy between the Thai coal plants and the Hongsa coal-fired power plant in Laos. Because this plant is seldom used at its highest capacity, one may therefore suspect that the benefits of this infrastructure do not offset its externalities, which include CO_2 emissions, local air pollution, deforestation (for open surface lignite mining), and pollution of water bodies (Deetes, 2015).

3.3. A Probabilistic Assessment

The analyses in Sections 3.1 and 3.2 show that droughts affect the availability of hydropower and thermoelectric resources and, by extension, production costs and CO_2 emissions. To determine the likelihood of the most extreme instances, we use monthly values of SDI at each hydropower and (freshwater-dependent) thermoelectric station and calculate the percentage of installed capacity under severe drought—using a threshold of SDI equal to −1. In Figure 8, each dot represents a month in the study period while the color represents the corresponding anomaly of cost (upper panel) and carbon dioxide emissions (bottom panel).

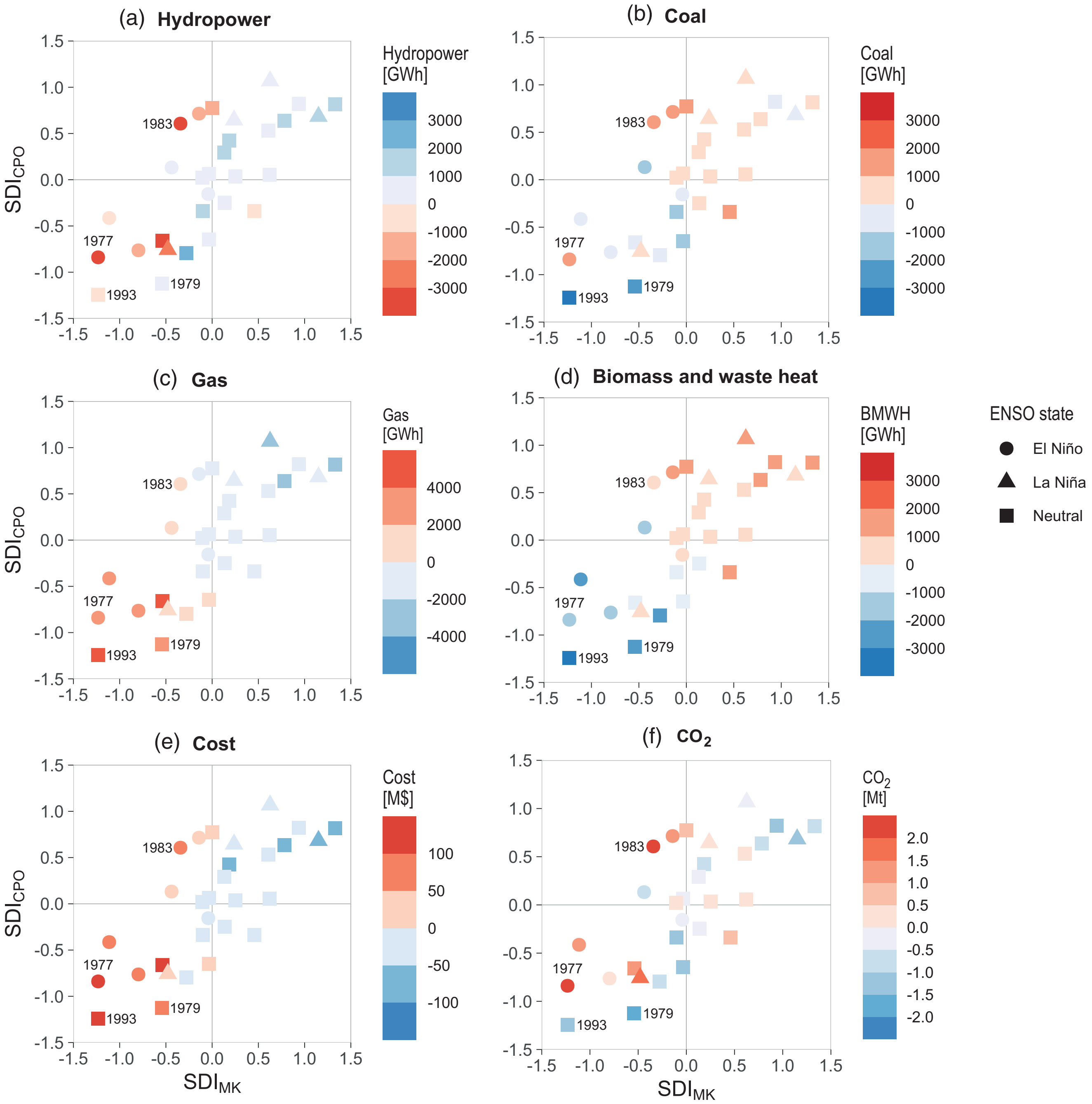

Figure 6. Scatter plots illustrating the relation between climate, water, and energy variables. The ENSO state is represented with three symbols, indicating El Niño (circle), Neutral (square), and La Niña (triangle) conditions. The state of Mekong and Chao Phraya basins is measured with the Streamflow Drought Index (SDI$_{MK}$ and SDI$_{CPO}$), reported on the horizontal and vertical axes, respectively. The behavior of the power system is quantified with the annual anomalies of hydropower, coal, gas, and biomass supply (a–d), productions costs, and CO$_2$ emissions (e–f). ENSO, El Niño Southern Oscillation.

Using kernel density estimation, we also calculate the univariate and bivariate probability distributions of hydropower and thermoelectric capacity impacted by extreme droughts. Beginning with the hydropower sector, the probability distribution indicates that it is more likely to have some dams (about 5% of the total installed capacity) under drought conditions than none—note that the median is larger than zero. The plot also shows that when about 25% of the capacity is under extreme droughts, the power grid experiences large monthly anomalies of both costs and emissions; a result of the increased reliance on thermoelectric

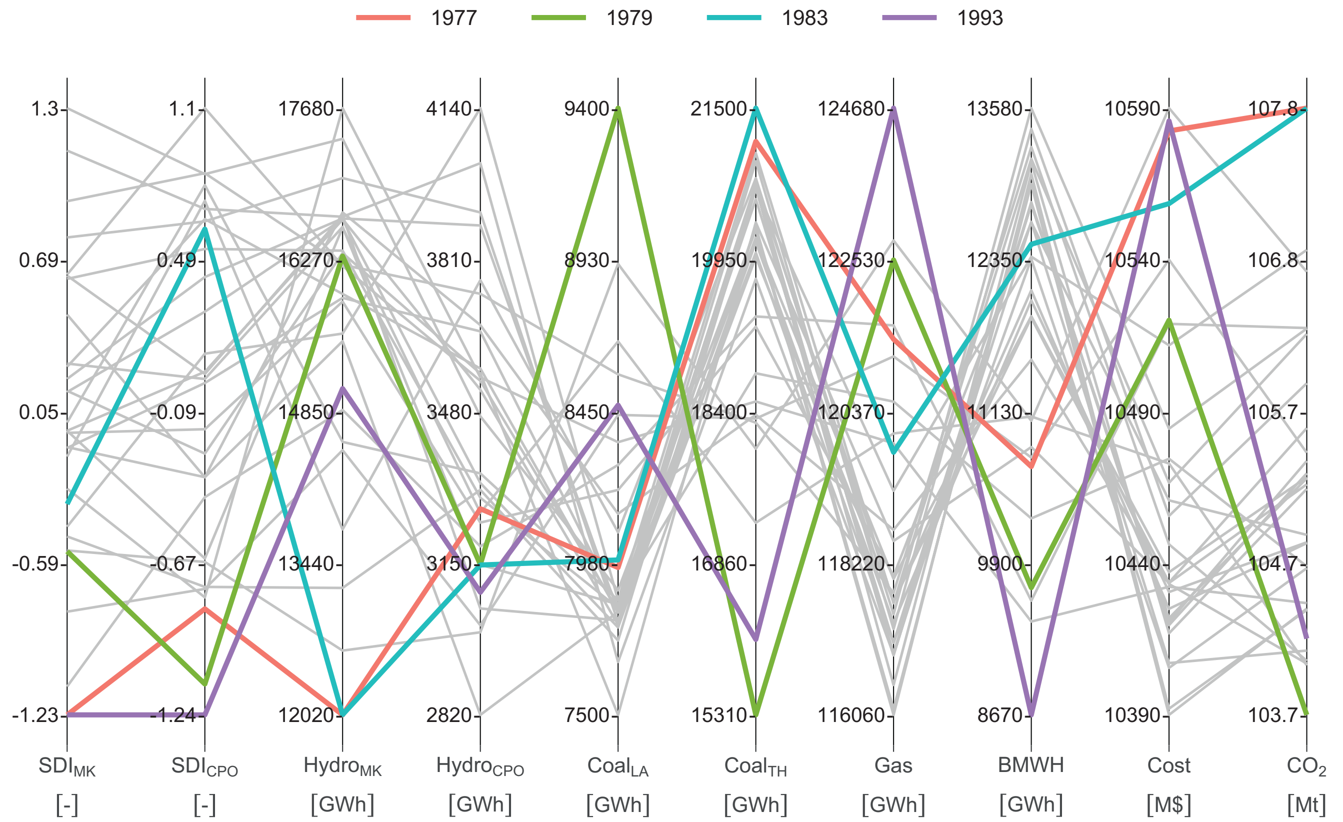

Figure 7. Parallel coordinate plot illustrating the relation between the state of Mekong and Chao Phraya basins (SDI$_{MK}$ and SDI$_{CPO}$), energy generation mix, production costs and CO$_2$ emissions. Variables are aggregated on an annual basis, so each line corresponds to a year. For the energy generation mix, we report the electricity dispatched from: hydropower plants located in the Mekong and Chao Phraya (Hydro$_{MK}$ and Hydro$_{CPO}$), coal plants located in Laos and Thailand (Coal$_{LA}$ and Coal$_{TH}$), gas plants (Gas), biomass and waste heat plants (BMWH). Note that the years highlighted here correspond to those illustrated in Figure 5. SDI, Streamflow Drought Index.

resources. As indicated by the probability distribution, such instances are not unlikely—the 25% threshold falls within the interquartile range. The thermoelectric sector has slightly higher chances of not experiencing extreme droughts. And yet, the exposure of just a small fraction of the cumulative capacity (from 10% to 25%) is sufficient to trigger a system's response, manifested by an increase in costs and decrease in emissions—recall that gas, the alternative to coal, is more expensive, but has a smaller carbon footprint than coal. Similarly to the case of hydropower, these instances fall within the interquartile range. In synthesis, both sectors are likely to be affected individually by short and intense droughts that disrupt the entire system's operations. Bringing the two sectors together under the bivariate distribution, we note that the probability of extreme droughts affecting hydropower and thermoelectric resources decreases sharply, especially for events impacting more than 50% of the installed capacity. As expected, these are the instances resulting in the largest impact on production costs and emissions.

4. Discussion

Our results reveal a cyclic pattern underpinning the relationship between climate, water, and energy variables in the Laotian-Thai power grid: as water availability in the Mekong and Chao Phraya River basins fluctuates between dry and wet conditions, in response to El Niño and La Niña conditions, so too does the power system behavior, whose generation mix must periodically lean toward thermoelectric and hydropower resources. The periodic fluctuations extend to annual production costs and CO$_2$ emissions, for which we observe a possible range of variability of ~250 M$ and 5 Mt per year. Taken from another perspective, water availability alone controls about 2.5% and 5% of the annual production costs and CO$_2$ emissions. The trickle-down effect of ENSO on power system performance is likely a consequence of the sensitivity of regulated

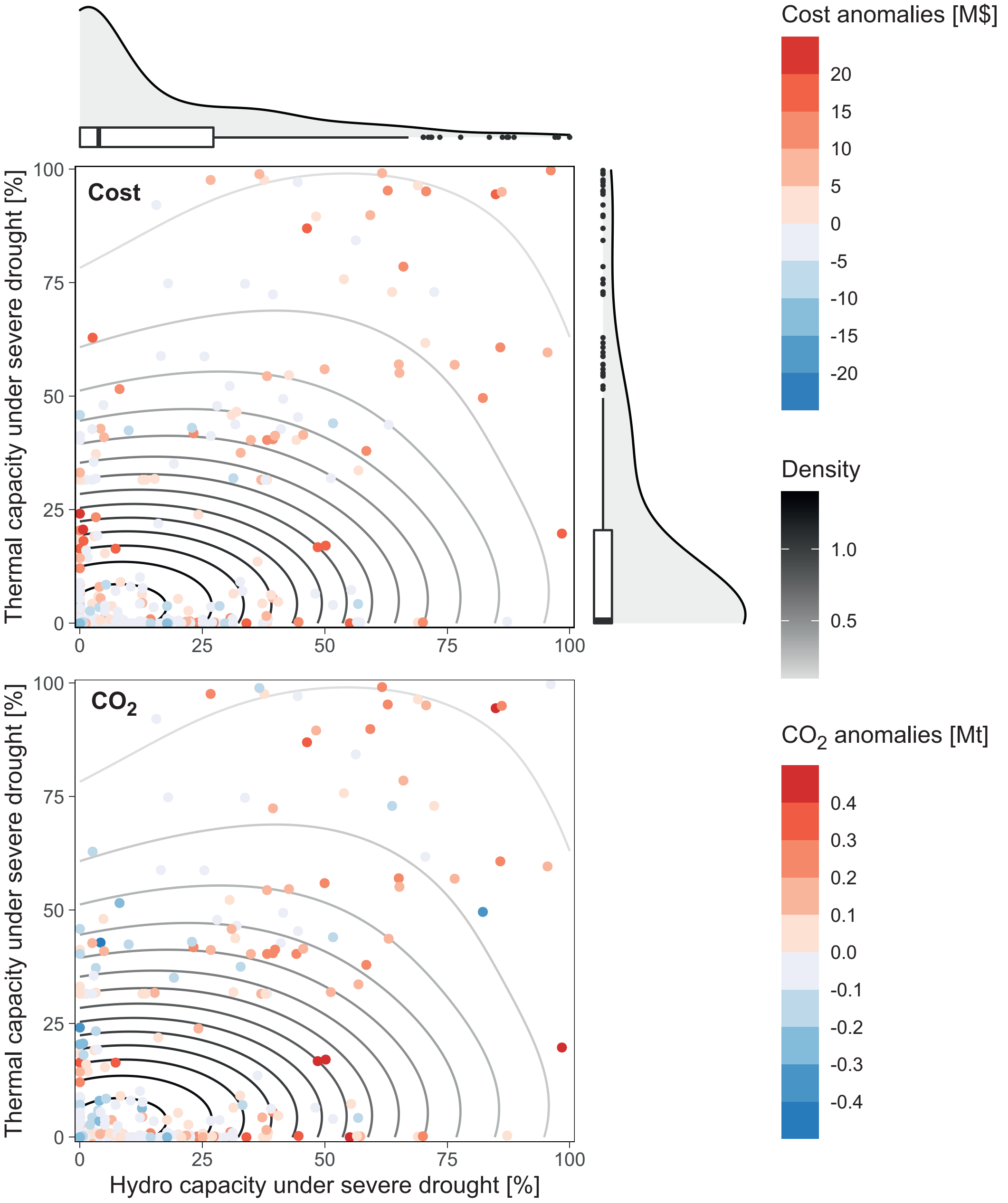

Figure 8. Probabilistic assessment of the most extreme droughts, along with their impact on costs and CO$_2$ emissions. In the upper panel, the horizontal and vertical axes report the percentage of hydropower and (freshwater-dependent) thermoelectric capacity under severe drought, defined as SDI < -1. (Note that the SDI is calculated at each specific station.) Each dot represents a month in the study period, while its color the corresponding (monthly) cost anomaly. The probability distribution (of being under severe drought) is estimated with a Gaussian kernel and illustrated on the top and top-right, for hydropower and thermoelectric resources, respectively. In the boxplots, the median is marked by a line inside the box, which represents the interquartile range. The whisker extends to 95th percentile, while outliers are outside this range. The bivariate distribution is represented by the isolines inside the plot. The bottom panel reports the same analysis, this time focused on carbon dioxide emissions. SDI, Streamflow Drought Index.

streamflow regimes to seasonal and interannual hydroclimatic variability (Ferrazzi et al., 2019). In theory, one would expect dams to smoothen inflow variability, thereby providing a steady electricity supply. But, in practice, the capability of a dam to buffer inflow variability depends on its design specifications and operating rules (Ng et al., 2017). Run-of-the-river hydropower dams, for instance, have limited storage capacity, so they cannot fully disconnect electricity generation from local hydrological conditions. The vulnerabilities we identified could be turned, however, into opportunities for better operations, because the teleconnection between ENSO and local hydrological conditions is one of the physical mechanisms on which subseasonal to seasonal forecasts rely. The range of variables that can be predicted is broad—for example, electricity demand, wind and solar availability or seasonal discharge—and so is the number of actionable decisions at the water-energy scale (Orlov et al., 2020). For example, operators could plan demand management strategies or purchase financial instruments, such as power futures, to hedge financial risks and protect end-users (ibidem). Another attractive option is to adopt reservoir operating policies that explicitly account for seasonal hydroclimatological forecasts, thereby making a more efficient use of the hydropower resources (Libisch-Lehner et al., 2019). All these opportunities will become even more important in the coming years as the Laotian–Thai grid will integrate more renewables and long-distance interconnections; a point on which we return later.

In accordance with previous studies (e.g., Byers et al., 2020), our work also shows that the response of a power system to droughts depends not only on their severity, but also on their spatial footprint. Because hydropower and thermoelectric plants are heterogeneously scattered across two river basins, the position of impacted units determines whether the power system must rely on coal, gas, or a combination thereof to offset the detrimental impacts of droughts. Yet, conclusions drawn on the grid's exposure and response to hydroclimatic variability should be taken with caution, owing to the nonstationarity in the ENSO-monsoon teleconnection. Analyses conducted over the past centuries—combining observed and paleo-reconstructed data—revealed that the strength of the teleconnection varied over space and time, alternating decades of weaker and stronger effects (Nguyen et al., 2020; Räsänen et al., 2016). An explanation for this behavior may be sought in the amplitude, temporal evolution, and spatial patterns of ENSO events. Recent decades, included in our study period, witnessed a change in ENSO dynamics, with warm events stronger than cold events in the eastern Pacific (Capotondi & Sardeshmukh, 2017). In turn, these eastern Pacific-centered events tend to constrain the descending branch of the Walker circulation within the Pacific domain, thereby modulating the summer monsoon in continental Southeast Asia (Singhrattna et al., 2005). If anthropogenic influence will exacerbate such phenomena—an hypothesis still debated (Cai et al., 2014; Perry et al., 2017)—we must then prepare for a drier summer monsoon, with less water available for power systems. A drier, and warmer, monsoon is also likely to increase air conditioning need and electricity demand (Parkpoom & Harrison, 2008), adding a further stressor to the water-energy system that certainly deserves further attention.

Future operating costs and CO_2 emissions will not only depend on joint water-energy management strategies and climatic conditions. They will also depend on Thailand's future Power Development Plans (PDP). According to the latest plan (EPPO, 2018), Thailand's electricity demand is expected to increase roughly 3% annually from 2018 to 2037. To meet it, Thailand is planning to reach in 2037 an installed capacity of 77,211 MW. This includes 56,431 MW of added capacity, since 25,310 MW are expected to be retired. If all moves as per plan, coal will be slightly sidelined (to 13% of the power generation), with gas, renewables, and energy efficiency contributing 53%, 28%, and 6% of power supply. As for the renewables, solar is expected to take a big leap forward, while wind targets, despite having reasonably good potential, are low (WoodMac, 2019). Hydropower will be further expanded, both locally and internationally. The two basins of particular interest are the Mekong and Irrawaddy. Our results for the existing Laotian–Thai interconnection suggest that the further reliance on monsoon rainfalls may undermine the expected benefits of these plans. For example, regional droughts could hinder the ambitious goal of cutting the CO_2 emissions intensity to 283 kg/MWh (EPPO, 2018). The issue gains further importance if El Niño-like conditions will become more frequent. Another point of potential concern is the heavy reliance on natural gas. Gas fields in the southern Gulf of Thailand are depleting, forcing Thailand to import gas from other countries—mostly Myanmar and Qatar (DBS, 2017). In turn, this may expose the grid to gas price volatility, warranting more research on the compound impacts of droughts and fuel price variability on grid operations (O'Connell et al., 2019).

Setting aside for a moment-grid operations, what is also worth discussing here is the fate of the Mekong and Irrawaddy River basins. The Mekong has already paid a substantial toll: dams built by Thailand, Laos, Vietnam, and China have affected the riverine ecosystems and altered hydrological processes (Arias et al., 2014; Hecht et al., 2019; Kondolf et al., 2018), impacting entire economic sectors on which the livelihood of millions depends (Sabo et al., 2017). In some cases, dam constructions have also increased greenhouse gas emissions (Räsänen et al., 2018) and forcibly displaced large indigenous communities (Scudder, 2020). If Thailand, and other countries, were to expand their hydropower fleet, we may expect further environmental impacts and tighter conflicts between economic sectors (Do et al., 2020;Yu et al., 2019). The Irrawaddy River basin may be next in line (Kattelus et al., 2015). The opportunities for a partial change of course are many. A first option would be to deploy more solar and wind plants (Schmitt et al., 2019). Eastern Thailand and central Myanmar, for example, have abundant theoretical potential of solar PV (Siala & Stich, 2016), offering a chance to make the 2018 PDP more sustainable. Likewise, wind targets could be further pushed. A potential game changer is the ASEAN Power Grid (APG): at this stage, Thailand and Laos are the only two countries largely relying on a cross-border power trade infrastructure, but things could change if more ASEAN countries were to have access to the same transmission infrastructure (Ahmed et al., 2017). The APG could connect load centers to more production sites, facilitating the integration of renewables within in Southeast Asia, while concurrently reducing pressure on river basins and CO_2 emissions.

5. Conclusions

In conclusion, our results indicate that hydroclimatic variability plays a key role in the operations of the Laotian-Thai power system. Electricity supply reliability does not seem to be at risk, while operating costs and CO_2 emissions vary in response to the hydrological conditions in the Mekong and Chao Phraya River basins. The two mechanisms controlling such response are reduced hydropower generation, mostly in the Mekong, and capacity derating at individual thermoelectric plants. Of particular concern is the spatial coherence of the two basins: regional droughts are frequent, forcing the power system to rely on gas and coal. In turn, these results suggest that long-distance power transfers may be doomed to temporary failures, especially if their design stems from a limited understanding of the interplay between global climate phenomena, such as ENSO, and local water-energy processes. Multimodel multiscale frameworks provide a methodological basis for characterizing this nexus, supporting operational decisions at the water-energy scale, and informing long-term capacity expansions.

Data Availability Statement

We provide all data, documented code, and results at https://github.com/kamal0013/PowNet-Thailand (http://doi.org/10.5281/zenodo.4040851). Due torestrictions, the only exceptions are theobserved discharge in the Mekong andthe dam design specifications.

Acknowledgments
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