Hydroclimatic change challenges the EU planned transition to a carbon neutral electricity system

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Abstract

EU Member States are progressively decarbonizing their electricity systems by replacing fossil fuels with renewable sources to achieve rapid greenhouse gases emissions reductions. While the planned decarbonized system will be more resilient to hydroclimatic change than existing water-dependent portfolios, water availability and temperature are still influential factors during this transition to a carbon neutral electricity system, with potential negative impacts on the economy and the environment. Here, we conduct a model-based analysis to assess the impacts of hydroclimatic change on EU decarbonization strategies in two regions, the Iberian Peninsula (IP) and the Danube river basin, characterized by a high share of water-dependent energy sources and expected to be highly affected by climate change. We find that, under the reference electricity system scenario for 2040 aligned with the EU climate and energy strategies, generation from fossil fuels increases, in particular from combined cycle gas turbine plants, to balance the reduction of hydro generation consistently observed in the hydroclimatic scenarios examined. This reduction, in conjunction with increased thermal plants shutdown events due to high water temperature especially in the IP, produces load cuts undermining the reliability of the electricity system. Moreover, increased fossil fuel use results in higher generation costs and carbon intensity, jeopardizing emissions reduction targets and ultimately slowing down the decarbonization process.

1. Introduction

The Green Deal has set the ambition for the EU to achieve zero net greenhouse gas (GHG) emissions by 2050, decoupling economic growth from the use of resources while ensuring that no person and no place is left behind (European Commission 2019). The decarbonization of the energy and electricity sector is recognized to be crucial to reach this ambitious target (Bruckner et al 2014, Davis et al 2018), with the increase in share of renewable energy sources (RES) in the continental power generation mix playing a major role in driving this transition (Fischedick et al 2011, Luderer et al 2012, 2014, Rockström et al 2017, Ueckerdt et al 2017).

Electricity systems are dependent on water for the functioning of hydro, thermal and nuclear power plants. Reduced water availability intensifies conflicts with other uses such as agriculture, drinking and household needs, industry, environmental protection, ultimately curtailing hydropower generation. Similarly, warmer water temperatures and, to a smaller extent, water scarcity, are harmful to thermal and nuclear power plant cooling: not only for minor efficiency losses in the cooling process, but also for the compliance with environmental regulations on receiving waters. The forced interruption of nuclear power plants in tandem with the curtailment of hydro, has been a recent regular occurrence in Europe (Rübbelke and Vögele 2011, Naumann et al 2015,}
van Vliet et al. (2016a). In 2003, several plants in France, the Danube river basin (DRB), and other regions were forced to reduce production or completely shut down because of high water temperature (Fink et al. 2004). The same situations have occurred in 2006 (Koch and Vögele 2009), 2015 and, most recently, in the summer of 2018 (Vogel et al. 2019), when several power plants were obliged to reduce power output or even to shut down in France, Germany, Switzerland, Finland and Sweden. During prolonged warm and dry periods, the combined effects on hydropower and thermal and nuclear plants result in economic damage, higher prices and conflict with environmental regulations (van Vliet et al. 2012, 2013, 2016a, 2016b, Pechan and Eisenack 2014, Behrens et al. 2017, Liu et al. 2017, Tobin et al. 2018, Byers et al. 2020, Kern et al. 2020, Yalew et al. 2020).

Even though the future electricity system will be less dependent on water resources due to the higher RES penetration in the generation mix and the substitution of obsolete thermal power plants with more water-efficient ones, extreme hydroclimatic events still pose a great risk, especially during the decarbonization transition (Khan et al. 2017, Peer and Sanders 2018, Zohrabian and Sanders 2018, Yalew et al. 2020, Gernaat et al. 2021), thus prompting the following challenges: what are the implications of EU energy policies in the transient period? Have the risks associated with changing hydroclimatic extremes been thoroughly evaluated in terms of generation costs and load cuts as well as with respect to sustainability metrics such as carbon and water intensity? Can EU energy policies be improved and adapted in order to robustly reach the emission targets while minimizing risks and guaranteeing reliability?

At present, these questions remain largely unanswered. In order to examine alternative future generation mixes and associated performance metrics of both energy and electricity systems, future scenarios and policies are designed and evaluated using energy system models (E3MLab and IIASA 2016, Capros et al. 2018). Yet, the prospective skill of these models, that are regularly used to inform and govern the transition to net zero GHG emissions, cannot be compared with their ability to capture observed data retrospectively mainly due to the traditionally independent and isolated management of water and energy sectors (Bazilian et al. 2011, Khan et al. 2017). Indeed, most of these models are not explicitly constrained by actual water availability and temperature; rather, they are calibrated to reproduce average observed hydroelectric generation over the year and assume a historical average hydrological regime. While this implicit representation of water resources in energy system models is accurate under average observed hydroclimatic conditions, it misrepresents natural variability and is not able to capture climate change impacts as it is grounded on the assumption of stationarity of the hydrological regime.

Here, we address this gap by coupling conceptual hydrological models at the power plant scale with a unit commitment model that allows the simulation of the power system. The resulting soft-integrated model is then used to assess the impact of climate driven hydrological change on the power system, both in techno-economic terms and environmental sustainability relative to a reference electricity system scenario (REF2040) where no water constraints are active. The power system is analyzed in the year 2040 in a decarbonization context under two climate scenarios, namely RCP 2.6 and RCP 8.5, which represent mild and extreme climate change in order to cover the whole range of plausible futures (van Vuuren et al. 2011). To quantify the role of natural variability, three different hydrological conditions are examined for each climate projections (i.e. median, dry and extremely dry). The scenarios considered allow a detailed characterization of extreme events, whose impacts assessment is crucial to ensure reliability of future energy systems (McCollum et al. 2020, Perera et al. 2020).

We focus our analysis onto two European regions (figure 1), the Iberian Peninsula (IP), specifically Spain and Portugal, and the DRB, namely Austria, Bulgaria, Croatia, Hungary, Romania, and Slovakia. These regions are classified as vulnerability hotspots as they are characterized by a high share of water-dependent energy sources that are expected to be highly impacted by climate changes when warmer and drier conditions will occur more frequently in the future (van Vliet et al. 2012, 2013, Tobin et al. 2018). In particular, first we examine differences between the currently projected generation mix and the one associated with future hydroclimatic conditions, considering both climate change and natural variability. Second, we analyze how these differences propagate to economic and sustainability metrics in order to understand whether the integrated modeling methodology adopted here allows a more robust planning of the future electricity system.

2. Methods

To assess climate change impacts on IP and DRB future electricity systems, we propose a soft-integrated modeling approach (figure 2) comprising three main steps: first, climate scenarios are converted into local air temperature and precipitation projections; second, these meteorological variables are used by hydrological models to estimate future water availability and temperature at the power plant scale; third, constrained on the output of hydrological models, the electricity system model is simulated. Finally, the impact of hydroclimatic change is
Climatic scenarios consist of precipitation and temperature projections deriving from simulations of the global climate model ICHEC-EC-EARTH and regional model RACMO22E, and made available to the public via the EURO CORDEX project (Jacob et al 2014). Under the considered combination of GCM-RCM models, the cumulative distribution function of the simulated precipitation achieved the best fit with respect to the distribution of observed data in the control period across the two regions. The models have been simulated using the RCP 2.6 and RCP 8.5 scenarios (Moss et al 2010, van Vuuren et al 2011) that represent a mild and extreme climate change scenario respectively. Even though RCP scenarios do not necessarily correlate with hydrological change (Hattermann et al 2018, Gao et al 2019), the extent of potential changes in mean temperature is bounded by the selected RCP scenarios and this has been proven to be the case also for precipitation projections in the regions examined (Rajczak and Schär 2017). Consequently, the RCP scenarios selected are expected to provide a lower and upper bound of potential future hydroclimatic impacts on the power system. The projected precipitation and temperature data are downscaled and bias-adjusted using a time-varying quantile mapping method (Boé et al 2007, Déqué 2007). The obtained climatic variables are used as input to compute daily streamflow at the basin outlet via the conceptual hydrological model HBV (Bergström 1995). The latter is a mass balance models based on four modules: snow, soil moisture, shallow layer and deep layer storage. The air temperature is used in an empirical conceptual model to map the atmospheric temperature into the daily temperature of the streamflow using a logistic regression calibrated for the region of interest (Mohseni et al 1998). Both evaluated comparing power system model simulation outputs under present and future hydroclimatic scenarios.
water availability and temperature are calculated at the closest basin outlet for each of the 167 hydroelectric, thermal and nuclear power plants analyzed (figure 1(a)). This assessment is performed for the future scenario, covering from year 2040 to 2060, and three relevant hydrological years are analyzed for each RCP, for a total of six future hydroclimatic scenarios. The hydrological scenarios describe median, dry and extremely dry hydrological conditions, and in the following are concisely reported as MED, DRY and EXT, respectively. As we focus on climate-induced vulnerability of water-dependent electricity systems, we do not consider wet scenarios; further research should assess the presence and magnitude of benefits deriving from such conditions as this would represent useful information for the evaluation of adaptation options.

Future power-plant specific water availability and temperature are used to constrain hydropower generation and thermal power plant cooling in the PRIMES-IEM power system model, which simulates the electricity system in the two regions with an hourly time step. PRIMES-IEM, relying on data and projections from PRIMES, an energy system model of the whole European Union, computes the commitment schedule, the power generation level, the contribution to each type of ancillary service for each thermal power plant and the power generation level for RES power plant by type, accounting for potential curtailment. The electricity system is simulated for the year 2040 in a decarbonization context bridging the EU2030 scenarios (E3MLab and IIASA 2016), developed for year 2030 in line with the ‘Clean Energy for all Europeans package’ (European Commission 2016) with the mid-century strategy for the year 2050, the ‘Clean Planet for all vision’ (European Commission 2018). We refer to the scenario without water constraints as REF2040 since this is to be considered the benchmark to be used in the quantification of the impacts. Activating constraints on water availability and temperature, and using different hydrological conditions, the impacts are obtained as differences with respect to the REF2040 baseline scenario in the generation mix, generation costs, magnitude of load cuts and carbon and water intensity.

A more detailed description of the methodology is reported in the supplementary material (available online at stacks.iop.org/ERL/16/104011/mmedia).

3. Results

3.1. Replacing hydro generation with fossil fuels

The projections generated via simulation of the power system models soft-integrated with 167 hydrological models over the six hydroclimatic scenarios result in a reduction of hydroelectric generation in both regions, which is compensated by a larger use of fossil fuels, and particularly combined cycle gas turbines (CCGTs) plants, to satisfy the electricity demand (figure 3, tables S2 and S3). Generally, hydroelectric reductions increase as hydrological conditions and climate scenarios become more extreme. The minimum reduction in hydropower generation for IP with respect to the REF2040 projections is 8 TWh (−16%) and occurs under RCP 2.6 MED, while the simulated hydro generation in the worst-case scenario (i.e. RCP 8.5 EXT) is around 30 TWh, which is only 41% of what produced under REF2040. The main replacement for the lost hydro generation is CCGT, with an increase ranging from 6 TWh (RCP 2.6 MED) to 23 TWh (RCP 8.5 EXT), while solids increase between 1 TWh and 2.5 TWh. Increased generation of nuclear power plants is around 1 TWh in all scenarios but under RCP 8.5 DRY, where high temperature forces some major nuclear plants to shut down. The remaining imbalance results in lost exports and load cuts. The results in the DRB show less sensitivity to the simulated hydrological and climatic scenarios, and similar impacts are obtained under all future scenarios but for RCP 8.5 EXT. Yet, significant differences are observed between these results and the REF2040 projections, with hydro generation reductions bounded between 8 TWh and 11 TWh (−10% to −14%), and up to 29 TWh (−37%) in RCP 8.5 EXT. In this case, the reduced hydro generation is compensated mostly by CCGT, which increase from +6 TWh to +8 TWh under all scenarios but for RCP 8.5 EXT (+21 TWh). Solids play also an important role in balancing the lost hydro generation, contributing from +1 TWh to +6 TWh in the case of RCP 8.5 EXT.

Overall, the projected shift from hydroelectric to CCGT generation in the different scenarios is not homogeneous (figure 4). Beside increasing the CCGT generation, some countries also rely on import from close countries. This is the case in Portugal and Spain where the latter employs CCGT also to balance the loss of hydro generation in Portugal. In the DRB, Slovakia, Hungary and Bulgaria increase their CCGT and solids generation to reduce imports and increase exports, especially towards Austria, where a significant reduction in hydro generation is observed.

3.2. Projected reliability and sustainability of the EU electricity system

As the power system model is solved with respect to a reference demand scenario, traditional probabilistic reliability metrics such as loss of load expectation and loss of load probability cannot be computed. For this reason, we examine the reliability of the power system by quantifying load cuts over the year and number of thermal power plants shutdown

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4 The electricity system scenarios were quantified before the nuclear phase-out in Spain by 2040 was declared. The reduction of nuclear earlier, may occur in lower reliance on cooling water, however hydro will still be significantly required to compensate for the higher share of variable RES in the system.
over each deterministic simulation representing the six hydroclimatic scenarios. These two metrics are negatively impacted, especially in IP: load cuts occur when power demand cannot be met since the hydro-power potential is already exhausted or the water temperature forces some thermal or nuclear power plant to shut down or reduce its power output; thermal and nuclear plants shutdown events are instead caused by extreme water temperature (figures 5(a) and (b)). For example, under RCP 2.6 EXT, IP hydroelectric reduction is about 33% and some plants are forced to shut down causing minor load cuts (0.033 TWh or around 1 h over the year). The highest number of shutdowns is expected under RCP 8.5 DRY, along with a 52% decrease in hydroelectric generation resulting in 2 TWh (or about 45 h per year) of load cuts (considering generation over a year). Under RCP 8.5 EXT, hydroelectric generation is further reduced to −59% but less nuclear power plant shutdowns are recorded as water temperature exceeds the threshold less frequently. The DRB is instead less affected by load cuts as they only occur under RCP 8.5 EXT and have smaller magnitude (0.1 TWh or approximately 3 h over the whole year). This is due to the fact that water temperature never limits the cooling of thermal and nuclear power plants in this region. The observed

Figure 3. Projected generation mix under the reference scenario (REF2040) and the six examined scenarios for IP and DRB.

Figure 4. Projected shift from hydroelectricity to CCGT for the six scenarios examined with respect to the reference scenario (REF2040).
load cuts are due to reductions in water availability, which becomes a limiting factor only in the north-western part of the basin (e.g. Austria) under the RCP 8.5 EXT scenario (figure 4).

The increased generation from fossil fuels to supplement the projected reduction in hydroelectricity affects significantly total generation costs of the future power system (figure 5(c)). Total generation costs in IP rise from 3 to a minimum of 34 billion euros (RCP 2.6 MED) and to a maximum 76 billion euros (RCP 8.5 EXT) because of the increased use of fossil power plants that have higher variable costs. System marginal price changes accordingly: from 7.4 EUR MWh\(^{-1}\) (REF2040) to 87 EUR MWh\(^{-1}\) and 196 EUR MWh\(^{-1}\) under RCP 2.6 MED and RCP 8.5 EXT, respectively. In the DRB, generation costs in the REF2040 scenario are higher than in IP due to the lower RES contribution to the generation mix. Similar to the IP case, they are expected to increase with the increased consumption of fossil fuels in the six considered hydroclimatic scenarios, almost doubling the REF2040 value under the RCP 8.5 EXT scenario. Consistently with generation costs, system marginal prices rise to around 115 EUR MWh\(^{-1}\), while they were equal to 103.4 EUR MWh\(^{-1}\) in REF2040.

Crucially, also the projected carbon intensities are jeopardized by the water-dependency of the electricity system in the six considered scenarios with respect to the expected values under REF2040 (figure 5(d)). In the IP, REF2040 carbon intensity is equal to 11 kgCO\(_2\) MWh\(^{-1}\), but it increases by 72% in the mildest scenario analyzed (RCP 2.6 MED), it doubles under RCP 2.6 EXT and RCP 8.5 MED, and becomes about four times larger under RCP 8.5 EXT (figure 5(d)). In the DRB, a residual dependence from CCGT and nuclear generation sets the REF2040 carbon intensity at 38 kgCO\(_2\) MWh\(^{-1}\), which is more than three times higher than in IP. As for the projected generation mix, in all scenarios we observe an increase of carbon intensity ranging from 48 kgCO\(_2\) MWh\(^{-1}\) (+26%) to 52 kgCO\(_2\) MWh\(^{-1}\) (+37%), except for
Finally, water intensities of the electricity system display a moderate change under the new hydroclimatic scenarios. The largest share of water withdrawal and consumption is due to nuclear power plants under all scenarios and in both regions (figure 6). Nonetheless, the differences observed in the generation mix of the two regions are translated into different water uses by the electricity sector. In particular, the water not withdrawn due to reduced hydro generation is used by CCGT in a consumptive and non-consumptive way. The total quantity of water withdrawn for electricity does not change significantly under all the scenarios and climatic conditions in both regions. However, increases in water consumption can be explained by increased CCGT generation. This trend is more evident in IP (from +5% in RCP 2.6 MED to +16% in RCP 8.5 EXT) than in DRB (from +2% in RCP 2.6 MED to +9% in RCP 8.5 EXT). Such differences can be attributed to the different value of consumptive water use of the REF2040 scenario: as for carbon intensity, in DRB fossil fuel technologies represent a larger share of the REF2040 generation mix than in IP and, therefore, their relative increase is smaller.

4. Discussion and conclusion

Climate change mitigation strategies require a fast transition from fossil fuel to RES, such as solar and wind, whose generation is less dependent on water availability and temperature. While moving towards a European fully decarbonized electricity system in 2050, the future generation mix is still expected to rely on water-dependent technologies as hydroelectric, nuclear and thermal power plants, to a limited extent. Energy policies and strategies are currently designed based on models that account limitedly for hydrological variability and climate change. As consequence, the impacts of hydroclimatic variability on the power system can be underestimated. Our study indicates that these impacts in IP and DRB are significant across all the metrics analyzed, emphasizing the importance of explicitly accounting for the energy-water nexus in the design of decarbonization policies.

In IP, the combined risks due to low water availability and high temperatures are likely to reduce the power system ability to meet the demand, resulting in major load cut events. While IP is almost fully decarbonized under REF2040, the changes in the generation mix induced by the projected water availability and temperature could lead to a resurgence of carbon intensity from 2% up to around 10% of 1990 levels (European Environment Agency 2017), substantially hindering and slowing down the transition. As for DRB, impacts are less dependent on the scenario analyzed but still produce substantial reductions of hydro generation and increases in CCGT with respect to REF2040, with consequent increase in generation costs and carbon intensity; more concerning impacts are observed under extremely dry conditions. Finally, under extremely dry conditions, the carbon intensity of the two regions’ electricity systems would be around EU projected average for 2030, substantially jeopardizing current emission reduction targets (European Commission 2020, European Environment Agency 2020).
Such results demonstrate the flaws of traditional energy and electricity system models and the resulting risk of misrepresenting future generation mix and carbon intensity, inducing an underestimation of impacts in terms of generations costs and GHG emissions. Particularly, as the EU aims for achieving carbon neutrality by 2050, the use of CCGT plants to compensate for lack of hydro will only be very limitedly possible (unless the power plants rely on hydrogen or new gases instead of natural gas); further, in a system which relies increasingly on variable RES, hydro is more frequently required to provide flexibility and storage to the power system. The potential evolution in hydro availability and storage due to hydroclimatic variability and other changes in water usage are currently only limitedly, if at all, reflected in energy system models.

We acknowledge here some limitations of the analysis that further research should be addressing soon. First, we do not reconsider planning expansion capacity neither we examine adaptation options in response to future hydroclimatic change (van Vliet et al 2016b, Szinai et al 2020). While additional exchanges with neighboring countries can explored in the short term, expansions of renewable and, potentially, storage capacity in order to better balance the reduction in electricity supply should be assessed as a long-term solution. Second, we neglected impacts of changes in wind and solar generation that might occur due to climate-induced variations in solar irradiation, cloudiness and wind speed (Craig et al 2019, Soares et al 2019, Solaun and Cerdá 2019, Gernaat et al 2021). Third, reservoir operations are modeled implicitly and giving priority to the agricultural demands—under the hypothesis of these latter being stationary. We believe future research needs to examine the potential for reducing combined risks and strengthening potential synergies by designing operating strategies reflecting the multi-purpose nature of many hydropower plants, following methods developed for large-scale reservoir operations modeling (Turner et al 2017b, 2020). Finally, we are aware that a more detailed representation of reservoir hydropower operations could affect the magnitude of the results, especially in dry and extremely dry hydrological conditions where reservoir storage capacity could better hedge against drought events. However, including dam operations into the analysis would require detailed operational (e.g. active storage capacity, minimum and maximum release) and normative (e.g. presence of environmental flow requirements, operating rules adopted by the managers) information for each of the 120 modeled hydropower plants that was not available for this study. Our results are anyway compatible with the findings of other recent works that rely on detailed models of reservoir operations (Turner et al 2017a, 2017b; Wan et al 2021). We recommend that future research should better investigate this aspect and the overall role of reservoir hydropower in adapting to future hydroclimatic conditions.

In conclusion, our findings, reinforcing previous literature results (Liu et al 2019, Vaca-Jiménez et al 2019), demonstrate the need of accounting for the effects of climate change and natural hydrological variability and the importance of examining multi-sectorial impacts of policies aiming to improve different sustainability indicators (Parkinson et al 2019, Khan et al 2020, 2021). The information provided by this type of analysis is indeed crucial to adapt EU energy policies and improve the planning of the transition to a carbon neutral electricity system (and overall energy system), while increasing its resilience and avoiding unnecessary adaptation costs.

Data availability statement

The hydrological conceptual model code is available on GitHub (https://github.com/mxgiuliani00/hbv) and the water availability and temperature scenarios produced for the 167 water-dependent power plants are available on Zenodo (https://doi.org/10.5281/zenodo.4339120).

A description of the electricity system model PRIMES-IEM is available at the following link: https://ec.europa.eu/energy/sites/ener/files/documents/ntua_publication mdi.pdf.

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