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Competing water uses between agriculture and energy: Quantifying future climate change impacts for the Portuguese power sector

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ABSTRACT

Climate change may increase water needs for irrigation in southern Europe competing with other water uses, such as hydropower, which may likely be impacted by lower precipitation. Climate change will also potentially affect the variability and availability of other renewable energy resources (solar and wind) and electricity consumption patterns. This work quantifies the effect of competition for water use between irrigation and hydropower in the future 2050 Portuguese carbon-neutral power sector and under Representative Concentration Pathway 8.5 climate change projections. It uses the power system eTIMES_PT model to assess the combined effects of climate change on the cost-optimal configuration of the power sectorconsidering changes in irrigation, hydropower, wind and solar PV availability. eTIMES_PT is a linear optimisation model that satisfies electricity demand at minimal total power system cost. Results show that, by 2050, climate change can lead to an increase in annual irrigation water needs up to 12% in Tagus and 19% in Douro watersheds (from 2005 values), with substantially higher values for spring (up to 84%). Combining these increased water needs with the expected reduction in river runoff can lead to a decline in summer and spring hydropower capacity factors from half to three times below current values. By 2050, concurrent water uses under climate change can reduce hydropower generation by 26–56% less than historically observed, mainly in summer and spring. Higher solar PV, complemented with batteries' electricity storage, can offset the lower hydropower availability, but this will lead to higher electricity prices. Adequate transboundary water management agreements and reducing water losses in irrigation systems will play a key role in mitigating climate impacts in both agriculture and power sector.

1. Introduction

Energy system models have been widely applied to design optimal low-carbon energy systems. Such systems rely on electrification and renewable power, mainly hydropower, solar PV and wind. However, renewable power supply is highly affected by climate change (Cronin et al., 2018) and thus, a carbon-neutral power future needs to be climate-resilient (Simoes et al., 2021).

Among the technologies potentially affected by climate change, hydropower has been one of the most studied, as hereby summarised. Behrens et al. (2017) developed an indicator of vulnerability of the electricity generation to water availability, also referred to in the literature as water to energy consumption. The authors included the water footprint of electricity production and concurrent water uses to discuss EU-wide power sector adaptation strategies by 2030. However, the focus of Behrens et al. (2017) analysis was on the impacts on thermal-based electricity generation, not considering the relevance of renewable energy sources (RES) in a fully decarbonized power system. van Vliet et al. (2016) developed a global analysis of water availability for the future power sector for both hydropower and thermal power plants cooling systems (water-energy-climate nexus). Zhang et al. (2018) reviewed the impacts of policy, climate change and water-energy-food (WEF) nexus on hydropower development at the global scale, while Falchetta et al. (2019) similarly focused on sub-Saharan Africa. The latter study showed that only a few countries have pursued a diversification strategy away from hydropower, even though some of the largest African river basins have experienced increased aridity in the last century.

Teotónio et al. (2017) analysed the impacts of climate change on hydro variability and its effects on the whole decarbonized Portuguese power system, while Jiang et al. (2021) designed an integrated

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framework to evaluate the robustness of renewable power systems under climate change, considering variation ranges, not only of streamflow, but also of PV and wind power output in a Chinese region. The interplay between hydropower and other power technologies under climate change was analysed by Gøtske and Victoria (2021) for Europe, showing that RES power expansion requires a higher seasonality and day-night switch of hydropower. The authors also conclude that climate change impacts on hydro resources will call for additional wind and solar power capacities in southern European countries. Although there is substantial literature on water (hydropower) and energy under climate change, they have been largely ignoring intersectoral perspectives, namely water competition between energy and other sectors (such as agriculture) under climate change.

Against this background, there is a distinct branch of literature focusing on water, energy and food. Islam et al. (2021) reviewed the scientific literature published from 1994 to 2018, covering 104 studies (out of 686 identified) focusing on water-energy interlinkages within the food system, including all the stages from on-farm production to consumer's plate and disposal of food waste. This review offers a comprehensive overview classifying these studies concerning their geographical scale (household, facility, city, state, river catchment, country, global, others) as well as, within the specific nexus (water-energy nexus, WEF nexus, water-energy-carbon nexus, water-energy-waste nexus, and water-related energy in food system). Mannan et al. (2018) reviewed several studies under the main categories of energy for water, water for energy, water for food, energy for food, regional nexus and life-cycle assessment (LCA), thoroughly identifying the interlinkages among each component.

These intersectoral studies are particularly important to support decision-making. Namany et al. (2019) review is performed regarding modelling approaches to support decision-making in water and energy resource management within WEF nexus, considering competing uses among sectors. The identified modelling approaches for resources management include mathematical optimisation, agent-based modelling and game theory. The decision-making methods are scenario analysis, integrated assessment modelling, robust decision making, LCA, computable general equilibrium models and data-driven models. The use of optimisation models is seen as the most appropriate to address trade-offs between sectors, at input and outputs stages, while simulation models may contribute to it, particularly when used interactively to translate synergies. Some studies have already pointed to the problematic consequences of not considering the synergies between water-energy-food sectors in potential strategies for conflict mitigation, namely Mayor et al. (2015), which present a case study in the Douro basin in Spain. The lack of coordination between energy and water resources management ended up in a problem shifting to the food system, where modernized irrigation schemes and investment lead to increased water-related energy consumption and higher energy prices.

Despite that the topic of competition between hydropower and irrigation has been widely covered in Islam et al. (2021), it gains a new urgency in face of the projected increase of water stress under climate change in specific regions, namely the Mediterranean (Cramer et al., 2018) or Central Asia (Bissenbayeva et al., 2021), particularly, where transboundary water management is present. Not enough is known about the magnitude and severity of impacts across the water-energy nexus, especially under climate change. Zeng et al. (2017) studied the interplay between hydropower generation and water needs for irrigation at the global level using machine-learning techniques and multi-source datasets. The authors found that currently, around 54% of global hydropower capacity (approx. 507 GW) competes with irrigation. While reservoir operations for hydropower production might support irrigation, there are also well-known cases where it reduces water availability for irrigated food production. In any case, existing research already indicates that water competition is expected to worsen in warmer regions since climate change will increase water use for irrigation due to accelerated evaporation, while simultaneously, hydropower will also be affected due to lower precipitation (Fader et al., 2016). Climate change projections for Douro and Tagus river basins (in Iberia Peninsula) show that by the end of the century these will likely suffer extreme multi-year droughts (Guerreiro et al., 2017b), and that minimum river runoff may be lowered by up to 40%, even without considering changes in current water uses (Forzieri et al., 2014). By the end of the century, in the whole Mediterranean region, irrigation demands are projected to increase by 4–18% for 2 °C and 5 °C warming scenarios, respectively (Cramer et al., 2018). In Southern Europe, such increase is even higher, between 17 and 28%, with and without the CO_2 fertilization effect, respectively, as projected by Fader et al. (2016).

The significant growth in water for irrigation demand by the end of the century raises causes for concern, particularly in regions where water is also key for ensuring the competitiveness of low-carbon electricity generation via hydropower. A combined assessment of the power system, highly sustained by hydropower and other RES, and water competition under climate change is still missing.

This paper examines the implications for a carbon neutral power system, when water is diverted for irrigation, lowering its availability for hydropower production. It addresses the mentioned research gaps by analysing to which extent the competition for water resources between agriculture and hydropower may affect the future Portuguese renewable-based power sector (2050), also considering climate change impacts on wind and solar PV availability, as well as on electricity demand. The eTIMES_PT model, previously developed by Amorim et al. (2020) and Fortes et al. (2022) is applied.

The methods used to estimate the future irrigation in Portuguese watersheds and hydropower and other renewables availability are presented in section 2, which also includes a description eTIMES_PT model and its main assumptions. Section 3 presents and discusses the results in terms of climate impacts on future irrigation, its consequent effect on hydropower availability and cost-optimal production, as well as, on the relative importance of different power technologies to meet electricity demand. Finally, section 4 summarizes the main conclusions.

2. Methods

The methods adopted in this study are structured in the following sequential steps (see also Fig. 1):

(i) estimation of additional irrigation water demand in the largest Portuguese and Spanish watersheds by 2050 due to climate change, using the global data set on potential irrigation water withdrawals simulated within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), for the RCP8.5 global warming scenario;
(ii) quantification of climate change impact on 2050 hydropower availability (i.e., capacity factors) considering not only lower precipitation but also concurrent surface water usage for irrigation in the transboundary Douro and Tagus watersheds, for both average and dry hydrological years; and
(iii) using the eTIMES_PT, technology cost-optimisation model for the Portuguese power system, to assess the interplay between different renewable power technologies, due to RCP8.5 climate impacts on RES power plants combined with the effect of concurrent water uses by 2050.

The eTIMES_PT model allows quantifying how concurrent water uses can affect the cost-optimal portfolio of the power sector regarding installed capacity, volumes of generated electricity in TWh and its costs for end-users. The model was chosen from a wide list of available models and tools as the TIMES models family are highly used to support energy-climate policy decisions, including the Portuguese Long Term Decarbonisation Strategy (Carbon Neutrality Roadmap 2050 – RNC2050) (Ministério do Ambiente e Transição Energética (República Portuguesa), 2019) and the Spanish Energy-Climate Action Plan (Ministerio para la

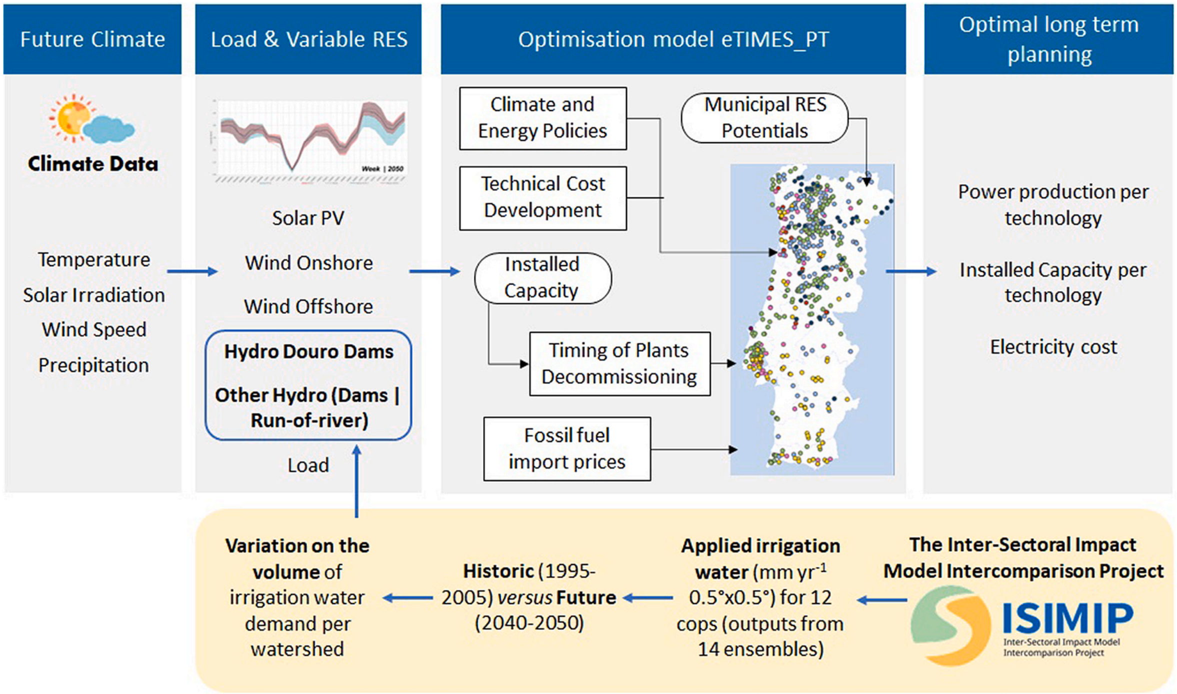

Fig. 1. Overview of the methodological approach used.

Transición Ecológica y el Reto Demográfico (Gobierno de España), 2020). These models generally do not consider climate change impacts, nor interactions between energy and other sectors of the economy that share common pools of natural resources, such as water, which may substantially change how the optimal future energy system should be thought (Fortes et al., 2022). TIMES, as other optimisation models, is particularly adequate to quantify the impacts of concurrent water uses under climate change, whereas other approaches such as simulation models (Brouwer et al., 2018) and/or multi-criteria analysis (e.g., as in Cetinkaya and Gunacti (2018) work) are more suited to address alternative options individually, once their magnitude is known.

Portugal is a very relevant case study since hydropower has a significant weight on national power generation (approx. 25% by 2020) and three main watersheds, which represent 60% of total hydropower installed capacity in Portugal (DGEG, 2021) are shared with Spain. In Portugal, agriculture is the major consumer of freshwater resources - 71.3% of the total water abstraction (2017 values (Eurostat, 2021c)) and around 32% of the Portuguese cultivated area is equipped with irrigation, which is above the European Union average of 9% (FAO, 2018). Both Iberian countries are known as climate hotspots regions, increasing the competition for water.

2.1. eTIMES_PT model and input parameters

This paper uses the eTIMES_PT linear optimisation model to quantify how concurrent water uses for irrigation and for hydropower can impact the configuration of the carbon-neutral Portuguese power sector by 2050, under future climate. eTIMES_PT, developed by the authors (Amorim et al., 2020; Fortes et al., 2022), is an application for the mainland Portuguese power system of the well-known and robust TIMES model generator. The ultimate objective of a TIMES model is to minimize the net present value of total electricity generation system costs (e.g., investment, fixed and variable operation and maintenance costs), complying with technological, physical and policy constraints, while simultaneously ensuring the satisfaction of the exogenous energy services demand. More information on the TIMES model generator can be found at Loulou et al. (2016) including the model equations.

eTIMES_PT finds the least-cost power system configuration, regarding power plants' installed capacity and generated electricity, to meet the exogenously defined electricity demand, considering a perfect foresight approach. The optimal solution complies with other modelling assumptions, such as greenhouse gas (GHG) emission caps and RES maximum techno-economic potentials.

In the present work eTIMES_PT runs from 2016 to 2060 in 4 and 10 years periods (i.e. 2016, 2020, 2030 … 2050, 2060), although the analysis is only focused on 2050. To properly deal with hourly, daily and seasonal variability of intermittent RES and the power demand profile, the model considers for each of the modelled years, the 4 seasons, two representative days (week and weekend) per season, disaggregated in 8 3-h clusters each (i.e., from 0h to 3h, 3h–6h, 6h–9h … 21h–0h, and so forth). This results in 64-time slices per year (4 seasons, 2 representative week/weekend days per season, 8 3-h clusters per day).

As all TIMES models, eTIMES_PT runs over a detailed technology database (in this case only for power generation and storage technologies) and considers several key inputs and assumptions, such as: (i) national electricity demand, (ii) technical potential for deploying new wind, solar and hydropower power plants and (iii) natural gas and biomass import prices. The considered power demand follows an increase from observed values of 169.7 PJ in 2016 to 235.6 PJ in 2050. These values were obtained from the Pack scenario in the legally adopted Portuguese Carbon Neutrality Roadmap (RNC2050) (Ministério do Ambiente e Transição Energética (República Portuguesa), 2019).

Table 1 presents a summary of the most relevant modelling inputs considered, that are further detailed in Fortes et al. (2022).

Since climate change impacts on RES power plants vary across the mainland Portuguese territory, the eTIMES_PT model explicitly represents each one of the 13 largest hydropower plants in the Douro river watershed, which correspond roughly to ~36% of national hydropower capacity (REN, 2020). The other hydropower plants (i.e., non-Douro) are modelled as generic hydropower technologies. A similar approach is used for onshore wind, solar PV power plants and thermal power plants.

Throughout all of this work it was considered that carbon neutrality will be achieved by 2050. This was included in eTIMES_PT model for all the modelled scenarios as a gradual shift of power supply towards 100% RES, departing from observed historical values of around 58.3% RES

Table 1
Techno-economic data for power generation technologies considered in eTIMES_PT for 2050 (based on Fortes et al. (2022)).

Technology	CAPEX (Euros$_{2016}$/MW)	Fixed OPEX (Euros$_{2016}$/MW)	Variable OPEX (Euros$_{2016}$/GWh)	Efficiency (%)	Techn. Capacity Factor (TCF) (%)[a]	Maximum tecno-economic potential (GW)
Wind Onshore	985	41.5	0	–	32	12
Wind Offshore	2365	75.6	0	–	50	>30
Solar PV (Roof)	1089	29.6	0	–	19	12
Solar PV (Utility)	687	23.4	0	–	22	13
Hydro	1075–1031[d]	12.1	0	–	30[b]	9.1
Pumped hydro storage	1031[d]	17.0	3.5	90	7[e]	
Waves	2074	74.4	0	–	27	7.7
Biomass Standard	2303	78.1	30.0	38	80	([f])
Biogas	3230	121.3	4.1	34	45	
Municipal Waste	2465	81.3	0	34	79	
CCGT[c] Small	1051	26.3	2.5	63	85	n.a.
CCGT Large	677	12.5	9.4	63	85	
CCGT with CCS[c]	1160	12.7	2.2	53	85	

n. a. – not applicable as Portugal does not have endogenous fossil resources.
Note: For all the power technologies is assumed a 4% discount rate.

[a] For variable RES (i.e., solar PV and onshore/offshore wind) the TCF are technology generic for Portugal, disregarding future climate conditions as considered by the RNC2050. The TCF for 2050 considers technology improvements.

[b] TCF represents mean hydrological conditions similar to 2011 estimated according to (Eurostat, 2021a, 2021b) data.

[c] CCGT: Combined Cycle Gas Turbine; CC: Carbon Capture.

[d] Hydropower installed capacity cannot be increased in eTIMES_PT because all technically viable hydropower plants will be deployed by 2025 following national policy directives.

[e] TCF considers median hydrological conditions for the period 2010–2019 according to (Eurostat, 2021a, 2021b) data.

[f] Maximum technical potential in GW is not considered. Bioenergy potential can be consulted in (Ruiz et al., 2015).

electricity (RES-e) in 202020 (DGEG, 2021) , 93.5% RES-e in 2030, 97.2% by 2040 and finally 99.8% by 2050.

This work builds on the previous work of Fortes et al. (2022) and Simoes et al. (2021) that considered climate change impacts on power demand and on maximum potential capacity factors for wind (onshore and offshore), solar PV and hydropower plants for eleven climate projections of under the Intergovernmental Panel on Climate Change representative concentration pathway RCP8.5.

These considered climate projections correspond to eleven combinations of global and regional climate models (respectively GCM and RCM) made available by the World Climate Research Programme's CORDEX initiative (www.euro-cordex.net). The combinations of RCM and driving GCM considered in the present analysis can be found in Appendix A.

The models were chosen according to: i. The availability of relevant climate variables, such as surface downwelling shortwave radiation, precipitation, near-surface wind speed, among other; ii. Satisfactorily simulate the climate over Europe; iii. Independent as possible from each other. The performance of the climate models was evaluated by analysing statistical indicators, namely: the mean bias, the mean absolute error and the root mean square error, assuming different combinations of climate variables and spatial averaging and considering the past reference data for the period from 1976 to 2005.

Each of these RCM-GCM model combinations provides estimations of the average climatological conditions over decades. Because of model differences, although all eleven combinations concur on the overall mean climatology, there are sometimes pronounced differences over some local regions. This is particularly the case for precipitation in North of Portugal and therefore it is relevant to consider all eleven projections instead of a mean. It should be mentioned that all of these eleven projections have an equal probability of occurrence. The variability of climate data was translated into eleven time-series of maximum capacity factors per technology applying distinct approaches, from machine learning to specially developed simulation tools, namely a hydrological model detailing each one of the largest hydropower plants for the Portuguese Douro River basin. Each methodology was validated by comparing models outcomes with historic data for 2014–2019 from the ENTSO-E Transparency Platform and from hydropower companies.

2.2. Additional water demand for irrigation in the larger Portuguese and Spanish watersheds, due to climate change

The climate change impact on water demand for irrigation was estimated for the whole Iberian Peninsula, i.e. Portugal and Spain, and for the three shared transboundary watersheds of Douro/Duero, Tagus (Tejo/Tajo) and Guadiana rivers (Fig. 2). In terms of hydropower only Tagus and Douro are further analysed in this study since close to 65% of hydropower production in Portugal mainland is located either in Douro or Tagus watersheds (DGEG, 2021). A significant portion of current irrigation in the Peninsula takes place in these three watersheds (Harmanny and Malek, 2019). Moreover, due to irrigation needs, there are already controversial water transfers from Tagus to the Jucar and Segura watersheds (Guerreiro et al., 2017a) and there have been mentions of other water transfer projects across watersheds in Iberia.

For this geographical scope, the potential irrigation water withdrawals (*pirrww*) data was obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) archive. ISIMIP is a well-known and robust "community-driven climate-impacts modelling initiative aimed at contributing to a quantitative and cross-sectoral synthesis of the differential impacts of climate change, including the associated uncertainties" (ISIMIP, 2021; Warszawski et al., 2014). The available *pirrww* is originally simulated at the global level, at a spatial resolution of 0.5° × 0.5°, through the impact model CLM45 (Community Land Model) along with the Climate forcing model GFDL-ESM2M (bias-corrected). *Pirrww* considers all aggregated crops under optimal irrigation and assumes loss-free conveyance, as well as unlimited surface water sources. The assessment of the model's ability to reproduce observed irrigation quantities is performed by using global remote sensing and in situ observational data sets (compiled by the Food and Agricultural Organization of the United Nations), as it is explained in Thiery et al. (2017).

Pirrww is originally provided per month in $kg.m^{-2}.s^{-1}$, which was then converted to $km^3.season^{-1}$ (i.e., by multiplying each grid cell by (a) the cell area in m^2, (b) the number of seconds in each season, (c) by 10^{-12} km^3 in 1 L, and (d) by dividing it by 3 months in a given season). Seasonal *pirrww* was then obtained by summing all the grid cells, over the three months of a season, within a specific region, i.e. at the country and watershed levels. Annual *pirrww* was obtained in a similar manner

Fig. 2. Geographical scope of analysis regarding additional water irrigation demand disaggregated by the river basin district in the Iberian Peninsula (as defined in Water Framework Directive). Adapted from EEA (2020).

summing the 12 months of the year.

The historical annual and seasonal *pirrww* was estimated as an average for the period 1985–2005, while the future *pirrww*, in 2050, refers to the average between 2040 and 2060 considering RCP8.5 scenario. A period of 30 years was considered for averaging datasets as, by convention, this time period is long enough to filter out any interannual variation, but also short enough to be able to show longer climatic trends. *Pirrww* simulations, as made available by ISIMIP, were obtained considering a constant CO_2 concentration (fixed at 2005 levels), and a dynamic CO_2 concentration, which increases with the RCP scenario. After 2005, all the available ISIMIP simulations consider a land-use scenario fixed at the year 2005, meaning there are no changes in the irrigation systems. Despite such model assumption, thus not allowing for other different irrigation scenarios, considering an irrigation system fixed at 2005 year allows to estimate the isolated impact of climate change under the high-emission RCP8.5 climate scenario.

The additional increment for irrigation (in %) between the future and historical averages of *pirrww* (while maintaining irrigation systems fixed at 2005) (equation (1)), results in the additional irrigation water demand in 2050, which was then used to assess the reduction in hydropower capacity factors.

$$\textit{Additional increment for irrigation} = \frac{(\text{Future} \quad \textit{pirrww RCP } 8.5) - (\text{Historical} \quad \textit{pirrww})}{\text{Historical} \quad \textit{pirrww}} \times 100\% \tag{1}$$

Table 2
Approach for assessing concurrent water uses impact on hydropower capacity factors.

Parameter		Douro Portugal	Douro Spain	Tagus Portugal	Tagus Spain
Current annual surface water abstracted for agriculture (hm^3/year) for each watershed and country		150.4 obtained by applying % for allocation of total national water use for agriculture from (Eurostat, 2021c) to watershed as in (APA, 2015) for 2017	2107.0 (Confederación Hidrográfica del Duero O.A., 2019) for surface water for 2017	257.2 obtained by applying % for allocation of total national water use for agriculture from (Eurostat, 2021c) to watershed as in (APA, 2015) for 2017	1759.0 (Confederación Hidrográfica del Tajo, 2014) for surface public and private irrigation
Current annual surface water abstracted for agriculture (hm^3/year) for each watershed		150.4 + 2107.0 = 2257.4		257.2 + 1759.0 = 2016.2	
Annual current river runoff (hm^3/year)	dry year 20th percentile	4833.0 (APA, 2019)		2411.0 (APA, 2019)	
	average year 50th percentile	8010.0 (APA, 2019)		6710.0 (APA, 2019)	
2050 current river runoff (hm^3/year)	dry year 20/25th percentile	4833.0 (APA, 2019) - 30% (Guerreiro et al., 2017)		2411.0 (APA, 2019) - 38/42% (Guerreiro et al., 2017)	
	average year 50th percentile	8010.0 (APA, 2019) – 25/28% (Guerreiro et al., 2017)		6710.0 (APA, 2019) - 29% (Guerreiro et al., 2017)	

2.3. Impact of additional water for irrigation on hydropower capacity factors

To calculate the impact of additional water for irrigation demand from the previous section into impacts on hydropower capacity factors, the following steps were taken (see also Table 2):

1. The current **annual and seasonal water volumes being used for irrigation** in hm^3 in both Douro and Tagus watersheds were estimated by reviewing available water management plans for Douro and Tagus, both in Spain and in Portugal;
2. The current irrigation water volumes for Douro and Tagus were translated into a **% of total current river runoff** for both an average and a dry hydrological year for each season of the year and in annual terms. The current Tagus and Douro annual runoff were obtained from the 2019 Portuguese State of the Environment Report ((APA, 2019) and seasonal runoff was computed using monthly runoff data from the Portuguese SNIRH – National Information System on Hydrological Resources for the hydrological monitoring stations of Ómnias for Tagus and Albufeira do Pocinho for Douro in Portugal. The approach used involved computing the relative weight of monthly runoff in the total annual runoff for both rivers for percentiles 20% and for average values which were assumed to represent dry and average hydrological years, respectively (note that percentile 50% data is not available);
3. The **2050 RCP8.5 irrigation water volumes** for the two transboundary watersheds were computed by adding the additional increment for irrigation in % from the previous section to the current irrigation water volumes;
4. The 2050 RCP8.5 irrigation water volumes for Douro and Tagus were translated to seasonal **irrigation shares of total future river runoff** also for both average and dry years considering future seasonal river runoff for both Douro and Tagus. These were obtained using the mean percentual change in discharge in 2050 estimated by Guerreiro et al. (2017a) departing from an ensemble of climate model projections from CMIP5 RCP8.5. 2050 mean percentual change considered both Guerreiro et al. (2017a) results for the two used methods (Modified empirical quantile mapping method and simple change factor approach) for percentiles 25 and 50, representing dry and average hydrological years, respectively. It was assumed that surface water abstraction for other uses, such as human consumption and industry, will not suffer significant fluctuations due to climate change, and thus will not cause additional changes in runoff. Currently, agriculture is the main responsible for surface water abstractions both in Portugal and Spain, 66% and 63%, respectively (Eurostat, 2021c);
5. The relative difference (in %) from current and future seasonal share of total river run-off was considered as a **proxy value of less water availability for hydropower generation and directly applied to the seasonal "historical" capacity factors** used in the eTIMES_PT model. The relative difference computed for Douro was considered for all conventional hydropower plants there located, whereas the Tagus value was considered for all non-Douro hydropower plants. It is assumed that Pumped hydro storage (PHS) plants are not impacted, as will be further detailed.

Table 2 presents the main parameters used. For simplification purposes, only the annual values are shown. It should be noted that in this work PHS plants were not considered to be affected by restrictions due to concurrent water uses, as their operation is less affected by river runoff. PHS plants circulate water from a reservoir to the turbines and back into the reservoir, and their operation profile is mainly motivated by profit and portfolio management concerns felt by the power companies that own them (IRENA, 2020). In Portugal, PHS plants currently represent 38% of total hydropower installed capacity (2019 data) (Eurostat, 2021a), which will not grow significantly (Ministério do Ambiente e Transição Energética (República Portuguesa), 2019).

It should be mentioned that currently, according to Portuguese water management plans, there is a ranking of priority for water uses, according to which water for human consumption is the top priority, followed by agriculture, then industry, maintaining ecological thresholds for minimum river runoff and finally hydropower water generation. Environmental authorities are responsible for conditioning certain water uses if droughts arise.

Thus, in eTIMES_PT model the following sets of scenarios were modelled:

- "Climate Constant" scenario in which future wind, solar, hydropower and electricity demand variability are not affected by climate change, considering: (i) "historical" capacity factors for hydropower, solar PV and wind and (ii) projected power demand, with historical load curves. It should be mentioned that "historical" capacity factors for solar and wind are the median recorded values between 2016 and 2019 (ENTSOE, n.d.), kept constant till 2060. For hydropower, capacity factors from 2011 were adopted since this was considered to be a representative climate constant year – i.e., equivalent to an average hydrological year since it as an Hydroelectric Productivity Index (HPI) near 1 (0.92 from (REN, 2020)).
- "RCP8.5" - eleven scenarios with capacity factors reflecting future climate conditions as in the projections of the eleven considered RCM under the RCP8.5 climate change pathway;
- "CWav" - eleven scenarios that consider both future RCP8.5 climate conditions and concurrent water uses for an average hydrological year;
- "CWdr" - eleven scenarios that consider both future RCP8.5 climate conditions and concurrent water uses for a dry hydrological year.

3. Results and discussion

This section presents the climate change impacts on the Portuguese power sector due to the estimated changes in the availability of renewable energy resources combined with water competition for hydropower and for irrigation.

3.1. Impact of climate change in water irrigation and hydropower capacity factors

Results show that, in annual terms, by 2050 and under RCP8.5 pathway, Portuguese irrigation water demand, with a historical annual average of 1.05 $km^3\ yr^{-1}$, is projected to increase between 4% and 10%, for a dynamic or constant CO_2 scenario from 2005 levels, respectively. Higher irrigation demand is estimated for Spain, between 27% and 30% above 2005 levels. The Douro is the Iberian watershed with the highest irrigation increase from 2005 values (~19%), followed by Guadiana and Tagus, with an increase of 12–16% and of 11–12%, respectively (Table 3).

Zooming at the seasonal level for both Douro and Tagus, the global annual increase in water demand for irrigation in 2050 under RCP8.5 is the result of two factors with different dynamics across seasons:

1) the **current seasonal irrigation profile**, with no irrigation needed in winter, small irrigation volumes required in autumn (0.03 km^3 for both Douro and Tagus, respectively) and spring (0.41 km^3 and 0.24 km^3 for Douro and Tagus), and most of the irrigation taking place over the summer (2.48 km^3 and 0.71 km^3 for Douro and Tagus);
2) **different climate change impacts across seasons**, with higher negative impacts, or in other words, increased irrigation needs, foreseen mostly for spring, with an additional irrigation demand by 2050 of 84–77% from 2005 irrigation levels for Douro and 45-43% for Tagus. Relatively smaller increases are foreseen for summer (+8–10% for Douro and +2–3% for Tagus), and none for winter. In autumn there are mixed trends for Douro and Tagus. Whereas for the

Table 3
Historical (average 1985–2005) and future (2050) water irrigation demand (km^3) per region, year, season and watershed.

Annual/ seasonal	Historical/2050 irrigation needs	Constant 2005 CO$_2$ concentration						Dynamic 2005 CO$_2$ concentration					
		EU	Portugal	Spain	Douro	Tagus	Guadiana	EU	Portugal	Spain	Douro	Tagus	Guadiana
Annual	Historical irrigation (km^3)	34.24	1.05	12.74	**2.92**	**0.97**	1.32	34.24	1.05	12.74	**2.92**	**0.97**	1.32
	2050 irrigation RCP8.5 (km^3)	41.22	1.15	16.14	**3.48**	**1.08**	1.48	40.16	1.08	16.50	**3.48**	**1.08**	1.53
	Δ2050/historical 2005 CO$_2$ (%)	*20%*	*10%*	*27%*	***19%***	***11%***	*12%*	*17%*	*4%*	*30%*	***19%***	***12%***	*16%*
Winter	Historical irrigation (km^3)	0.01	0.00	0.01	**0.00**	**0.00**	0.00	0.01	0.00	0.01	**0.00**	**0.00**	0.00
	2050 irrigation RCP8.5 (km^3)	0.09	0.00	0.06	**0.00**	**0.00**	0.00	0.09	0.00	0.06	**0.00**	**0.00**	0.00
	Δ2050/historical 2005 CO$_2$ (%)	*642%*	*525%*	*752%*	**-**	**-**	*−100%*	*642%*	*525%*	*752%*	**-**	**-**	*−100%*
Spring	Historical irrigation (km^3)	7.21	0.24	3.59	**0.41**	**0.24**	0.47	7.21	0.24	3.59	**0.41**	**0.24**	0.47
	2050 irrigation RCP8.5 (km^3)	9.72	0.31	5.95	**0.76**	**0.34**	0.64	9.45	0.30	5.93	**0.73**	**0.34**	0.64
	Δ2050/historical 2005 CO$_2$ (%)	*35%*	*30%*	*66%*	***84%***	***45%***	*36%*	*31%*	*24%*	*65%*	***77%***	***43%***	*36%*
Summer	Historical irrigation (km^3)	26.09	0.77	9.05	**2.48**	**0.71**	0.85	26.09	0.77	9.05	**2.48**	**0.71**	0.85
	2050 irrigation RCP8.5 (km^3)	30.64	0.82	10.07	**2.69**	**0.73**	0.85	29.92	0.77	10.45	**2.72**	**0.74**	0.90
	Δ2050/historical 2005 CO$_2$ (%)	*17%*	*6%*	*11%*	***8%***	***2%***	*0%*	*15%*	*0%*	*15%*	***10%***	***3%***	*5%*
Autumn	Historical irrigation (km^3)	0.93	0.04	0.09	**0.03**	**0.02**	0.01	0.93	0.04	0.09	**0.03**	**0.02**	0.01
	2050 irrigation RCP8.5 (km^3)	0.76	0.02	0.06	**0.03**	**0.01**	0.00	0.70	0.02	0.06	**0.03**	**0.01**	0.00
	Δ2050/historical 2005 CO$_2$ (%)	*−18%*	*−48%*	*−29%*	***16%***	***−65%***	*−78%*	*−24%*	*−55%*	*−33%*	***4%***	***−65%***	*−78%*

former an increase in irrigation needs is expected (+16-4%), for the latter, precipitation can increase and 2050 irrigation needs can be lower by less 65% from 2005 irrigation levels.

In short, there will be an increased need for water for irrigation by 2050 for the two watersheds in all seasons, except for: (i) winter when no irrigation will be necessary and (ii) autumn for Tagus, where less irrigation will be needed, due to increased precipitation during that

Table 4
Summary of the impacts of future water irrigation demand (RCP8.5 for variable CO$_2$ concentration) in future hydropower capacity factors considered in eTIMES_PT.

Watershed	Historical		2050				
	Water for irrigation (hm^3)	Share of water irrigation in total runoff (A)	Water for irrigation (hm^3)	Share of water irrigation in total runoff (B)		Variation of the hydropower capacity factor (CW wtr RCP8.5 scenario) (A-B)	
				MEQM[a] approach	CF[a] approach	MEQM[a] approach	CF approach[a]
Average hydrological conditions							
Douro							
Annual	*2257.4*	*28%*	*2690.7*	*46%*	*45%*	*−18%*	*−17%*
Winter	0.3	0%	0.3	0%	0%	0%	0%
Spring	795.9	38%	1466.1	102%	97%	−64%	−59%
Summer	1448.5	125%	1570.6	194%	186%	−69%	−61%
Autumn	12.6	1%	14.6	1%	2%	−1%	−1%
Tejo							
Annual	*2016.2*	*30%*	*2243.4*	*47%*	*47%*	*−17%*	*−17%*
Winter	–	0%	–	0%	0%	0%	0%
Spring	284.4	17%	412.1	33%	33%	−17%	−16%
Summer	1711.1	200%	1747.5	281%	278%	−82%	−78%
Autumn	20.7	2%	7.3	1%	1%	1%	1%
Dry hydrological conditions							
Douro							
Annual	*2257.4*	*47%*	*2511.8*	*74%*	*80%*	*−28%*	*−33%*
Winter	0.3	0%	0.3	0%	0%	0%	0%
Spring	795.9	61%	1153.2	151%	153%	−91%	−92%
Summer	1448.5	169%	1479.4	287%	295%	−119%	−126%
Autumn	12.6	1%	4.5	1%	3%	0%	−2%
Tejo							
Annual	*2016.2*	*84%*	*2403.2*	*161%*	*160%*	*−77%*	*−77%*
Winter	–	0%	–	0%	0%	0%	0%
Spring	284.4	52%	523.9	184%	105%	−132%	−53%
Summer	1711.1	449%	1855.3	786%	642%	−336%	−192%
Autumn	20.7	4%	24.0	10%	3%	−7%	0%

[a] MEQM (Modified empirical quantile mapping) and CF (Monthly Change Factor) approaches used to estimate future river monthly discharge in Guerreiro et al. (2017a).

season and watershed. It should be mentioned that the current irrigation volumes for Tagus and Douro obtained from ISIMIP are slightly different from the ones obtained from the official data for Portugal and Spain (in section 3). This could be because ISIMIP results from modelling which is not completely in line with observed data. In any case, only the percentual difference between irrigation volumes was used and not the absolute values.

The range of presented values for percentual variation in water demand for irrigation reflects the two constant and dynamic CO_2 concentration scenarios from ISIMIP. It should be mentioned that the effect of higher CO_2 concentration remains one of the largest uncertainties of climate change impacts on agriculture. In theory, crops (such as wheat, rice, soybeans, as well as trees) increase their photosynthesis and water productivity under higher CO_2 concentration and thus these plants reduce their water requirements. However, the effect of CO_2 concentration can be offset by higher temperatures and altered precipitation patterns, and this impact varies according to the crop type (Fader et al., 2016). Due to large uncertainty, crop modelling experiments usually consider these two CO_2 scenarios, and the crop response is most likely within the range of these two simulations. These justifications could, perhaps, explain the results observed, for example, for Spain, where slightly higher water demand is projected under a dynamic CO_2 scenario.

The variation of annual and seasonal water needs for irrigation leads to a higher share of annual abstraction for irrigation purposes over the total annual runoff across the whole Douro and Tagus watersheds. By 2050, and for average hydrological conditions, this would mean an increase of 17–18% for Douro and 17% for Tagus. Under dry conditions, this increase is even more prominent, up to circa 28–33% and 77%, respectively for Douro and Tagus (Table 4). A significant part of these outcomes are also due to the expected future decrease in river runoff under RCP8.5 as estimated by Guerreiro et al. (2017a). By 2050, due to climate change, there could be an annual runoff reduction of 30% for Douro and 38–42% for Tagus on dry conditions. On average hydrological conditions, run-off reduction is estimated to be 25–28% less for Douro and 29% for Tagus.

At seasonal level, as previously mentioned, no change is anticipated for winter. However, during the summer, water volumes required for irrigation will increase substantially by 2050. Nowadays, already in summer, current irrigation volumes are higher than runoff (Table 3). Note that this is the result of a simplified approach that does not consider intra-day runoff variability, nor the water storage done in those two watersheds. Agriculture activities currently located in both Douro and Tagus rely on substantial water storage reservoirs, some of which are also hydropower plants. The combination of increased water demand for irrigation and lower river runoff in summer is found to lead to an increase in the share of water irrigation in total runoff, ranging from the current value of 125% to 186–194% in 2050 in Douro for average conditions (from 169% to 287–295% in dry hydrological years). For Tagus, this share increases from 200% to 278–281% (average conditions) and from 449% to 642–786% (dry conditions). This roughly translates in a reduction of the summer hydropower maximum potential capacity factor for Douro and Tagus of 61–69% and 78–82%, respectively, for an average hydrological year. For dry hydrological condtions, the computed reduction in hydropower capacity factors is bigger than 100%, which is translated, as noted in the next section of this paper, as no hydropower generation being possible in summer by 2050.

Therefore, the higher impact on hydropower maximum potential capacity factors is for the summer season. For spring a reduction of capacity factors around 59–64% and 16–17% is obtained in Douro and Tagus hydropower plants, respectively, for an average hydrological year (less 16–17% and 52–132% in Douro and Tagus for a dry year). As mentioned before, there are no reduction in capacity factors for winter. Autumn reductions are substantially lower, i.e. up to 7% less for the two river basins.

3.2. Hydropower production

Fig. 3 shows the differences in hydropower plants generation for the year 2050, with and without water competition (for the three sets of modelled scenarios, each comprising eleven climate projections). Even without considering water competition (RCP8.5 scenarios), the role of conventional hydropower and PHS plants varies across the different seasons of the year, following the seasonal fluctuations of: (i) hydrological resources, (ii) demand for power and (iii) the availability of other RES technologies (e.g., wind and solar PV).

Fig. 3 corroborates the findings of existing literature (Fortes et al., 2022; Teotónio et al., 2017) since climate change will reduce conventional hydropower production in Portugal, in all seasons, except autumn. Even without concurrent water uses, the RCP8.5 scenarios, climate change can decrease conventional hydropower production in winter up to 52% less than in the climate constant scenario and 47% and 35% less in spring and summer, respectively. Although all RCP8.5 climate projections point towards a drier southern Iberian Peninsula (Guerreiro et al., 2017a, 2017b), in the Douro watershed located in the north of Portugal, a set of climate models foresees an increase in precipitation in autumn. Since most of the hydropower production is in Douro, this impacts autumn conventional hydropower production,

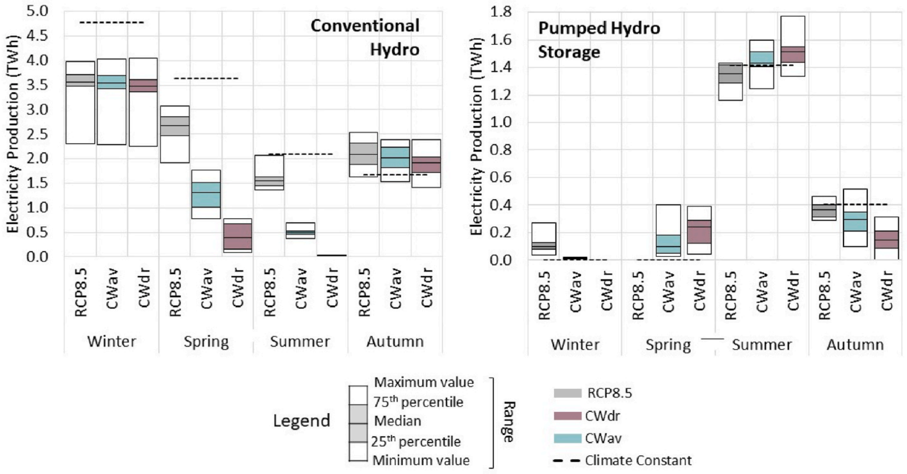

Fig. 3. Electricity generation from hydropower (left) and PHS (right) in 2050 for the RCP8.5 climate projections without water competition (RCP8.5) and with water competition (CWav and CWdr scenarios for average and dry hydrological conditions, respectively).

where in fact autumn hydropower generation increases in 2050 by 25% in median terms across all modelled climate projections. Note that both Climate Constant and RCP8.5 scenarios were run only for average hydrological conditions.

When considering cumulatively water competition for irrigation for both dry and average hydrological conditions, the output of conventional hydropower production is lowered even further, mainly in summer and spring. This is because there will be no increased irrigation needs in winter and only a minor increase in autumn for Douro (Table 4), due to higher precipitation in the season. summer is the most affected season and under dry hydrological conditions for RCP8.5 warming pathway, there will be no hydropower operation in both Douro and Tagus. As mentioned in section 3, this is the result of ensuring water for irrigation and for maintaining thresholds of river runoff for ecological purposes, which will have priority over hydropower generation. Therefore, it was assumed that environmental authorities will not allow hydropower operation by 2050 in summer whenever the irrigation volumes exceed river runoff. According to the obtained results, this will be the case whenever there is a dry year. Under average hydrological conditions, summer hydropower operation will decrease by −68% in median terms when considering cumulatively climate change and concurrent water uses (CWav *versus* RCP8.5). The corresponding decrease in spring is of 51–85% (−1.35 to −2.27 TWh) for average and dry years (CWav and CWdr *versus* RCP8.5).

The impact on conventional hydropower plants generation is not replicated for PHS plants. PHS plants operate as providers of daily and seasonal water storage services, also complementing variable solar and wind power plants profiles (IRENA, 2020). As previously mentioned, contrary to conventional hydropower plants, PHS plants are not directly impacted by river runoff. The 2010–2019 annual historical capacity factor of the two types of hydropower technologies for Portugal range between 17 and 46% for conventional hydropower and only 5–10% for PHS (based on Eurostat (2021a, 2021b) data). This corroborates the minor role of PHS plants and their lower dependency on precipitation and hydrological conditions. In fact, 2012, the driest year of the 2010–2019 series (with a conventional hydropower annual capacity factor of only 17%) had the highest PHS output (10% capacity factor). Such behaviour of PHS is reflected in the results here presented – in Fig. 3, the two seasons with the highest PHS output under dry conditions (spring and summer) are also the seasons with the lowest conventional hydropower generation. It should be mentioned that PHS in eTIMES_PT is mainly generating electricity during night hours in the absence of solar resources for PV power plants. This is similar to the PHS operation profile described in IRENA (2020).

3.3. Total power production

The impacts of climate change on water resources availability have a direct impact on the hydropower generation, affecting the overall power mix in 2050. As depicted in Fig. 4, the lower role of hydropower when considering climate change (Constant Climate *versus* RCP8.5) affects the cost-effectiveness of solar PV, onshore and offshore wind and biomass power plants in the 2050 carbon-neutral power sector in Portugal.

Comparing RCP8.5 scenarios with a historical average hydrological year (Climate Constant scenario), it is found that climate change can lead to a reduction of annual global hydropower production in 2050 of 8–26% (−17% in median terms). This reduction can be further exacerbated to less 26–56% annual hydropower production than in Climate Constant (less 34–47% in median terms) if concurrent water uses are considered as in the CWav and CWdr scenarios. Hydropower represents 15% of total electricity generated in Portugal in 2050 in the Climate Constant scenario, only 13% in RCP8.5, 10% in CWav and 8% in CWdr, in median terms. This reduction in hydropower generation is mainly offset by PV coupled with electricity storage in batteries, with a small but important contribution from biomass and, to a less extent, natural gas power plants.

The effect of climate change and concurrent water uses varies across the four seasons of the year (Fig. 5). At seasonal level, CWav and CWdr have a lower hydropower production than RCP8.5, mainly in summer and spring, and an increase in autumn. The interplay between hydropower, solar PV, wind and biomass is determined naturally by the lower hydropower availability, but also by the different seasonality of variable, intermittent solar and wind resources. As detailed in Fortes et al. (2022), onshore wind capacity factors are higher during winter nights and very low during summer at midday, with intermediate values during autumn. Offshore wind availability, in turn, does not have a significant intraday variation, with capacity factors being very high during both autumn and winter, and rather low during the whole summer season. It should be noted that the considered power demand varies across seasons, ranging from 24.4 TWh in winter, 20.4 TWh in spring, 21.0 TWh in summer to 20.7 TWh in autumn.

Because of this, the reduction of hydropower generation in summer is mainly offset by an increase of solar PV and biomass (in CWav and CWdr) and in spring by PV, onshore wind and biomass. In autumn there will be an increase in precipitation and consequently in hydropower output for average hydrological conditions. This is a combined result of the increase in production from conventional hydropower minimised with the lower output of PHS (see Fig. 3). When considering concurrent water uses in autumn, conventional hydropower generation can have either an increase or a small reduction of ~1% in their capacity factor (Table 3), leading to small variations in solar PV in CWav and CWdr. In winter, concurrent water uses do not impact the capacity factor of conventional hydropower plants. However, there is a slight reduction in total hydropower generation due to lower activity of PHS (Fig. 3), since its operation is less cost-effective than solar PV. This is a result of higher variable PHS OPEX (Table 1).

In Fortes et al. (2022), it was found that wind offshore was the most cost-effective power technology for ensuring a reliable power mix in Portugal, in 2050, considering climate change. In this work, by considering also concurrent water uses, it is now found that the

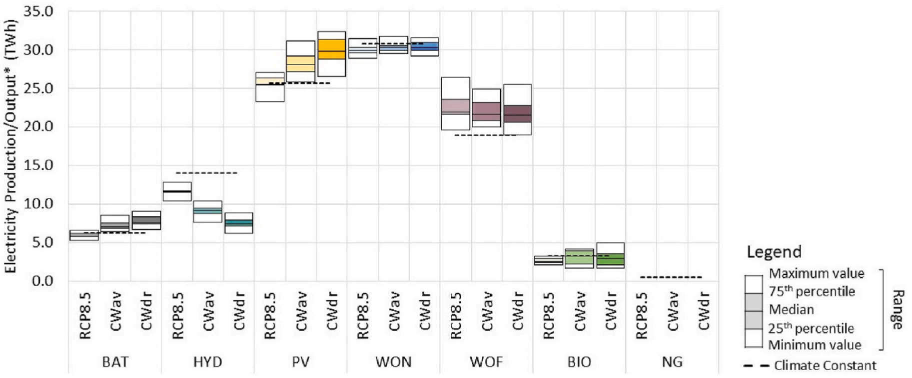

Fig. 4. Annual electricity generation per technology in 2050 for the climate constant scenario (dotted line) and for the RCP8.5 climate projections without water competition (RCP8.5) and with water competition (CWav and CWdr for average and dry conditions). BAT: Batteries; HYD: Hydropower; PV: Solar PV (utility and roof); WON: Wind Onshore; WOF: Wind Offshore; BIO: Biomass; NG: Natural Gas. * Electricity output refers to battery operation, since strictly speaking batteries do not generate electricity.

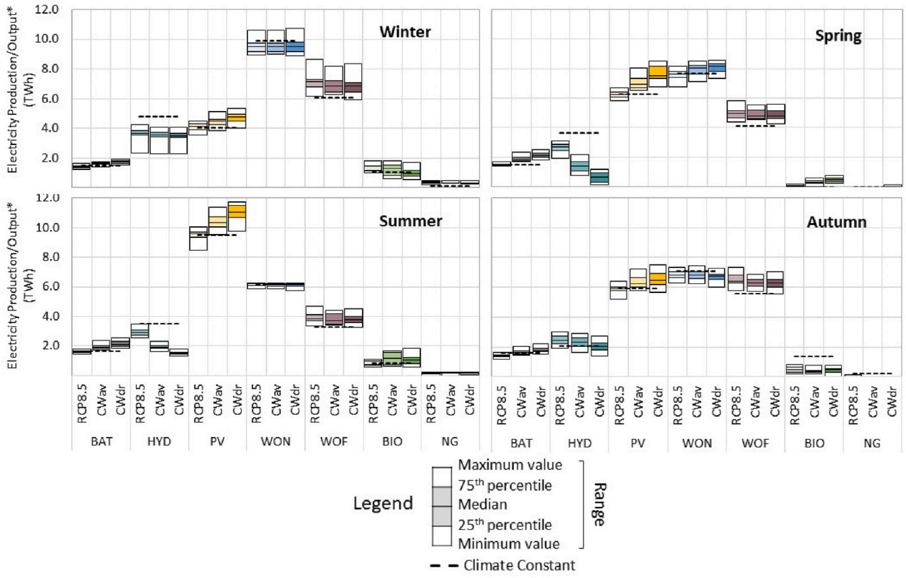

Fig. 5. Seasonal electricity production per technology in 2050 for the climate constant scenario (dotted line) and for the RCP8.5 climate projections without water competition (RCP8.5) and with water competition (CWav and CWdr for average and dry conditions). BAT: Batteries; HYD: Hydropower; PV: Solar PV (utility and roof); WON: Wind Onshore; WOF: Wind Offshore; BIO: Biomass; NG: Natural Gas. * Electricity output refers to battery operation, since strictly speaking batteries do not generate electricity.

cost-effectiveness of wind offshore becomes lower, since the seasons where hydropower is negatively impacted, i.e. summer and spring are also the ones with the lower wind offshore capacity factors. Thus, solar PV complemented with electricity storage in batteries becomes more cost-effective. It is worthy to mention that in all modelled scenarios it is not possible to invest in new conventional hydropower and onshore wind, which already reached the maximum techno-economic potential by 2050.

The range of possible electricity generation outputs obtained when the eleven climate projections are considered (reflecting the eleven different climate models) leads to a variation on the solar PV output of circa 3.8 TWh for RCP8.5 and 5.3–5.8 TWh for CWav and CWdr, respectively. Wind offshore output can vary by 6.9 TWh for RCP8.5 and 5.0–6.5 TWh for water competition (CWav and CWdr) scenarios. Onshore wind, biomass and batteries have a lower variability in power output across the sets of climate scenarios for RC8.4, CWav and CWdr.

Thus, solar PV has an important role to deal with the combined effects of concurrent water uses and climate change, although there is some degree of uncertainty on how much this could be. It should be underlined that all the eleven climate projections are equally representative from the point of view of significance, i.e., they have an equal probability of occurrence. Neves et al. (2021) also concluded that for the Southern of Portugal, solar energy is the most well adapted energy vector, and that interannual variability in the water sector and solar based technologies should be used to better integrate energy and water management.

Despite these conclusions, eTIMES_PT outcomes should be looked carefully. They allow to understand the response of power sector to climate change and water availability, but they do not reflect the behaviour of firms' investment decisions, the market options, nor guarante power system reliability. The operation of hydropower reservoirs for example, is the result of power dispatch strategies, which in most cases is not a function of hydrology, but of power market dynamics.

3.4. Impact of concurrent water uses in power generation installed capacity and power costs

The range of possible generation output from solar PV plants is also reflected a range of possible 2050 installed capacity (Fig. 6). Solar PV is the power technology with a widest variation in installed capacity, with 14.6–17.1 GW installed in RCP 8.5, 16.0–19.3 GW for CWav and 16.5–20.1 GW for CWdr. This directly impacts the variation of batteries' installed capacity, which can achieve up to 11.8 GW for CWdr. In the case of wind power, the variation of installed capacity across the eleven climate models considered in RCP8.5, CWav and CWdr is much lower, particularly for onshore wind which all the tecno-economic potential is cost-effective, regardless of the considered climate model.

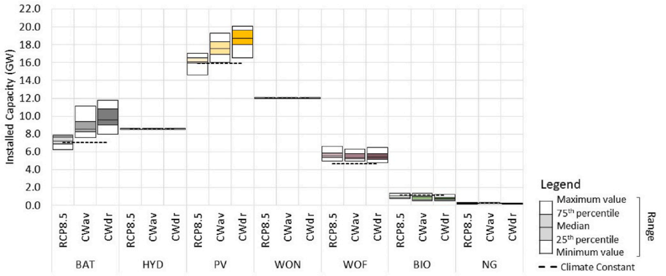

Fig. 6. Installed electricity generation capacity per technology in 2050 for the climate constant scenario (dotted line) and for the RCP8.5 climate projections without water competition (RCP8.5) and with water competition (CWav and CWdr for average and dry conditions). BAT: Batteries; HYD: Hydropower; PV: Solar PV (utility and roof); WON: Wind Onshore; WOF: Wind Offshore; BIO: Biomass; NG: Natural Gas.

Table 5
Impact of 2050 median unitary electricity cost for end-users per season and scenario (values for CWav and CWdr represent the percentual difference wtr to RCP8.5 scenario).

Scenario	Unit	Winter	Spring	Summer	Autumn	Annual
Climate Constant	€'16/ MWh	85.4	22.6	87.2	114.3	77.2
RCP8.5	€'16/ MWh	132.4	38.2	87.9	52.9	78.0
CWav	ΔRCP8.5	−1%	16%	8%	−11%	1%
CWdr	ΔRCP8.5	−5%	32%	11%	−12%	2%

All of these factors play a role in determining the unitary electricity costs (see Table 5) to end-users, which is computed by the model as a result of the combination of investment and maintenance costs, fuels, CO_2e shadow cost (when applicable), and delivery costs. Thus, the different unitary costs of electricity are a result of the cost-optimal electricity generation mix, shown previously. Mature renewable technologies such as hydropower, onshore wind and solar PV tend to induce lower unitary costs, while thermal power plants, i.e., natural gas and biomass lead to higher costs, due to fuel consumption and CO_2e shadow cost. In the Climate Constant scenario autumn represents the season with the highest electricity costs, explained by the higher thermal power production, which is not offset by the significant availability of solar PV as in summer or the higher hydro and onshore wind power production as in winter. Simply by considering climate change impacts, there is an increase in RCP8.5 unitary costs from Climate Constant, varying across the seasons of the year. Note that autumn is the exception, in this season RCP8.5 scenarios costs do not increase compared to Climate Constant due to the expected precipitation increase in some scenarios in the North of the country, and consequently, higher hydropower availability. In CWav and CWdr scenarios, considering concurrent water uses leads to a further increase in electricity unitary costs in spring (more 16–32% than in RCP8.5) and summer (8–11% more than in RCP8.5) and a decrease in autumn and winter. This reflects mostly the availability of conventional hydropower, i.e., less hydropower leads to the deployment and use of other more expensive power technologies, particularly biomass and the installation of more battery storage. Despite this, in annual terms, concurrent water uses will not cause a major cost increase (higher by only 1–2%).

4. Conclusions

This paper uses the case study of Portugal to assess the impact of concurrent water uses between irrigation and hydropower on a 2050 carbon-neutral power sector configuration. Three sets of scenarios, each covering eleven climate projections within the RCP8.5 pathway, were modelled in the eTIMES_PT optimisation model, with and without considering concurrent water uses, for both average and dry hydrological conditions.

It is feasible to have a carbon-neutral power system in 2050 in Portugal considering water competition under climate change, which can nearly halve annual hydropower production (in median terms) face to current conditions. However, the operation of such system in summer and spring will be challenging, particularly in dry years when additional irrigation needs may lead to no water availability for hydropower production (i.e., reduction of capacity factors above 100%), increasing electricity unitary costs. Solar PV coupled with electricity storage in batteries is found to be the most cost-effective option to compensate the lower hydropower production, although other power technologies, such as biomass and wind onshore also play a role.

These outcomes pinpoint the relevance of developing not only an integrated analysis, but also of planning approaches, holistically addressing both power generation and water needs for other economic activities. This is fundamental for ensuring future water security, reliable power production and sustainable agriculture in all seasons.

It should be mentioned that the obtained results do not account for water losses in irrigation conveyance systems, whose magnitude is determined by meteorological conditions. In addition, different alternative scenarios regarding future irrigation schemes could be considered. These are highly linked with political and financial wills, such as switching crops according to the climate conditions, to water availability, or due to other economic interests. Overall, a higher level of policy attention is required for the interconnected topics of irrigation, hydropower and climate change.

One of the limitations of this work is that there are substantial uncertainties on the data and approach herein used to estimate the current share of irrigation water in total river runoff, and on how this can affect the water availability for hydropower operation. A way to further improve this assessment would be to use hydrological models, to more accurately translate the effects of irrigation increase in hydropower operation. It is also important to underline that the analysis does not address sub seasonal shorter periods when water shortages can occur, as only "representative" seasons are considered. Because of this, the translation of concurrent water uses into reductions of hydropower capacity factors can eventually be too pessimistic. It was also assumed that pumped-hydro storage plants are not affected by additional irrigation water demand. Although this is currently valid, it could change under extreme water scarcity, with such plants also being required to restrict their operation.

Despite of the limitations and areas for improvement, the developed work provides useful insights into the interplay between water for irrigation and for hydropower production under climate change. This topic will increasingly gain relevance in the coming years and the proposed approach can be applied to other watersheds in other regions.

CRediT authorship contribution statement

Patricia Fortes: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Sofia G. Simoes:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Teresa Armada Brás:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Filipa Amorim:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A1 presents information on the eleven climate projections considered in the present analysis for RCP 8.5.

Table A1
Climate model chains used in the present analysis

#	Regional Climate Model	Driving GCM (Global Climate Model)	Short name	Institue responsable for RCM
1	**CLM**com-CCLM4-8-17	CNRM-CERFACS-**CNRM-CM5**	**CLM_CNRM-CM5**	Climate Limited-area Modelling Community (CLM-Community)
2	**CLM**com-CCLM4-8-17	ICHEC-**EC-EARTH**	**CLM_EC-EARTH**	
3	**DMI**-HIRHAM5	ICHEC-**EC-EARTH**	**DMI_EC-EARTH**	Danish Meteorological Institute
4	**DMI**-HIRHAM5	NCC-**NorESM1-M**	**DMI_NorESM1-M**	
5	**MPI**-CSC-REMO2009	MPI-*M*-**MPI-ESM-LR**	**MPI_MPI-ESM-LR**	Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology
6	**IPSL**-INERIS-WRF331F	IPSL-IPSL-**CM5A-MR**	**IPSL_CM5A-MR**	Institut Pierre-Simon Laplace
7	**KNMI**-RACMO22E	ICHEC-**EC-EARTH**	**KNMI_EC-EARTH**	Royal Netherlands Meteorological Institute, De Bilt, The Netherlands
8	**KNMI**-RACMO22E	MOHC-**HadGEM2-ES**	**KNMI_HadGEM2-ES**	
9	**SMHI**-RCA4	ICHEC-**EC-EARTH**	**SMHI_EC-EARTH**	Swedish Meteorological and Hydrological Institute, Rossby Centre
10	**SMHI**-RCA4	IPSL-IPSL-**CM5A-MR**	**SMHI_CM5A-MR**	
11	**SMHI**-RCA4	MOHC-**HadGEM2-ES**	**SMHI_HadGEM2-ES**	

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