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Study on US-EU Integrated Power and Water Systems Modelling

PP-06161-2017

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Research and Innovation

Study on US-EU Integrated Power and Water Systems Modelling

European Commission
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1 Scope of the study

The scope of the present study was to investigate the interdependence between the future water availability and the power system as well as where possible to analyse the possibilities for flexibility both on the energy and water side. The analysis attempted to quantify these interdependences as well as their economic and environmental impacts.

In order to study the variety of relationships, four different case studies were chosen and analysed within the European territory:

1. Iberian Peninsula: multi-country study of the dependence of the power system on water availability in a region with high share of variable RES

2. Danube river basin: multi-country study of the dependence of the power system on water availability in a region with a power generation mix relying on nuclear, hydro and thermal power stations, and relatively more limited variable RES resources

3. Alpine region: multi-country study of the dependence of the power system on water availability with focus on the Swiss Alpine region

4. Adda River basin: study of the optimal use of interrelated hydropower plants within a single river basin

In order to undertake the analysis a soft-integration framework based on existing water and energy models operating at different spatiotemporal scales was created. This allows to assess the impact of water availability to the power system operation, and explore potential benefits of finer scales and more detailed water processes' characterization over existing energy system models.

2 Geographical scope of the study

Four different regions (three multi-country and one small river basin regions) were selected as case studies for the integrated power and water systems modelling analysis:

- **Iberian Peninsula.** This region is characterized by two dominant climate types: the oceanic climate seen in the Atlantic northern and western coastal region resulting in even temperatures with relatively cool summers, and the Mediterranean climate, which characterizes most of Portugal and Spain (southern and eastern areas), and presents various precipitation and temperatures depending on latitude and position versus the sea. There are also more localized semi-arid climates in central Spain, with temperatures resembling a more continental Mediterranean climate, while only a small fraction of the territory in the South-East (Almeria) presents a very arid climate. This variability is reflected also in the water availability with frequent drought episodes produced by high temperatures combined with low precipitation, which often lead to critical reduction in the storage of water reservoirs. The Iberian Peninsula is therefore a good framework to implement the water-energy nexus because (i) its water and energy systems present strong interdependencies; (ii) climate change might affect some of these interdependencies; (iii) the two countries (i.e. Spain and Portugal) share both the hydrological and the power system, with small exchanges with other countries.

- **Danube region.** The Danube is Europe's second longest river and flows through 10 countries. The Danube basin has a warm continental climate in average. In the west (upper basin) Atlantic climate is predominant, while it is Mediterranean type in the south-west (ex-Yugoslavian countries). Based on an extensive Danube Basin analysis update carried out in 2013 the Danube River Basin Management Plan - Update 2015 Draft reaffirms that hydropower generation, physical modification and overexploitation of water bodies, and diffuse pollution from agriculture have been identified as significant pressures with cross border impacts. Moreover, in future water scarcity and drought are forecast to occur by a number of Danube countries impacting thermal energy production and hydropower.

- **Alpine region.** The Alps play a crucial role in accumulating and supplying water to the continent and are recognized as the 'water towers of Europe [1]. This area displays a variety of climatic conditions: the valleys have a *warm temperate climate* (even *sub-Mediterranean* in the South) while, as altitude increases, *continental* and *alpine climate* become prevalent. The Alpine system is characterized by a highly varying terrain elevation, which provides a huge hydro-power potential exploited through a series of small to medium artificial reservoirs. The intensive hydropower production relies on the high hydraulic head of the system and on water availability that is threatened by global climate change. Due to the complexity of the system, we also focus on a high-resolution case study (i.e. Adda river basin).

- **Adda river basin.** It is a sub-region of the Alps geographic area; a more detailed analysis has been carried out to better deal with the complexity of such an intertwined water-energy system.

The regions analysed are reported in Figure 1, while Figure 2 shows the countries involved in the analysis.

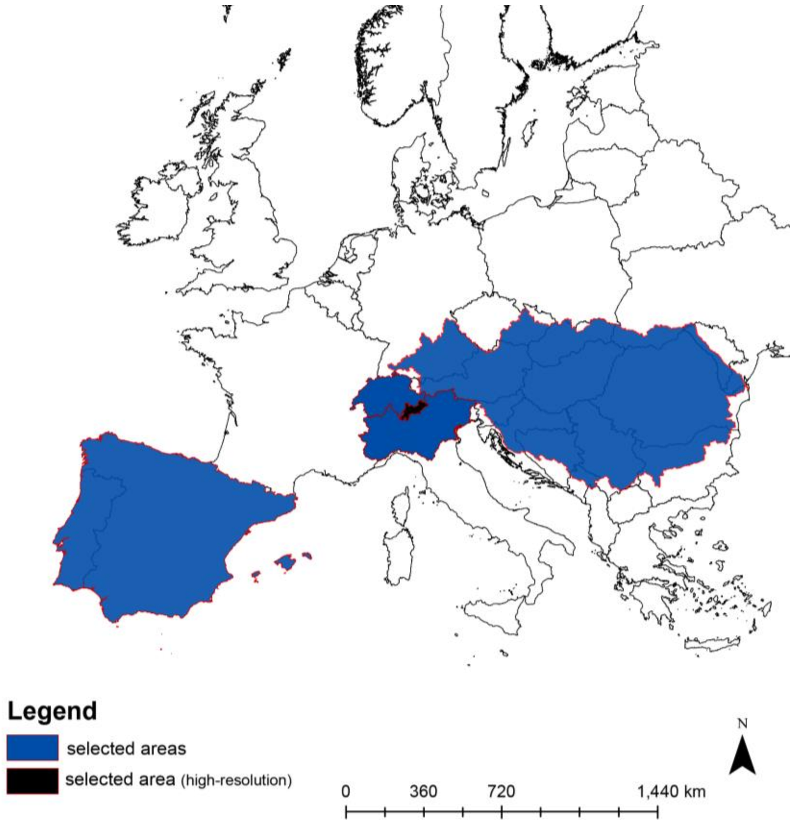

Figure 1 : Areas selected for the analysis

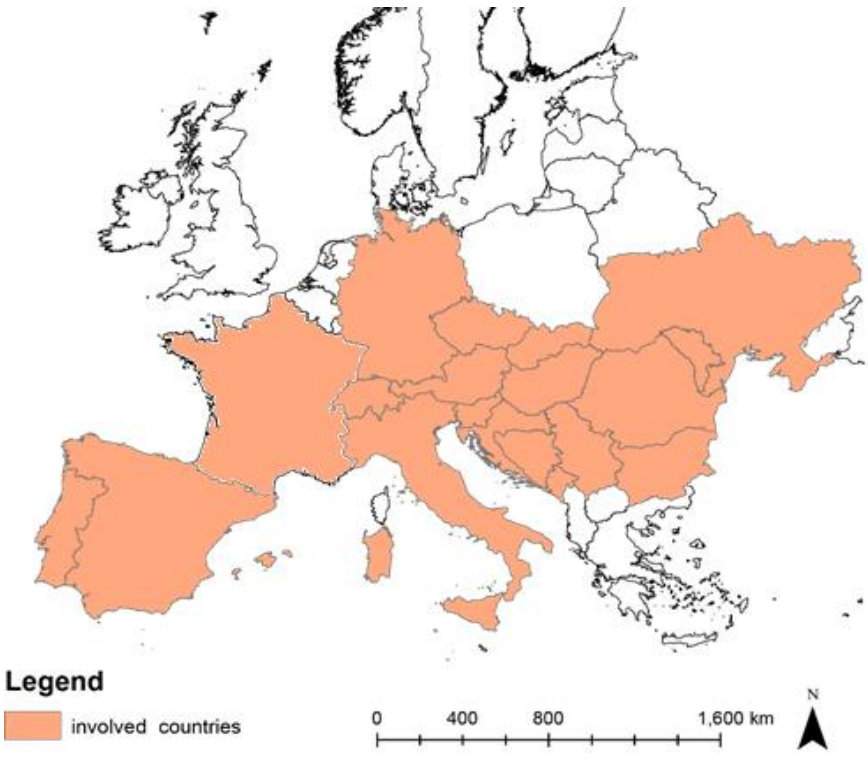

Figure 2: Countries involved in the analysis.

2.1 Iberian Peninsula

The Iberian Peninsula covers a 583,254 km^2 area and its topography varies considerably throughout the region (Figure 3, [2]). Mountain ranges mainly run from west to east, reaching altitudes of approximately 3,000 m above sea level (a.s.l.), and profoundly influence the hydrological system of the Peninsula (i.e., the river network and the spatial configuration of its seven major river basins) [3][2]. Of the seven major river basins, five flow towards the Atlantic Ocean (i.e. Miño-Sil, Duero, Tajo, Guadiana and Guadalquivir basins), and only two end into the Mediterranean Sea (i.e. Jùcar and Ebro basins) (Figure 3, left panel).

The annual precipitation is characterized by a southeast-to-northwest gradient [4][5], due to the location between the Ocean and the Mediterranean Sea and the heterogeneous topography, as well as to large atmospheric circulation patterns. The annual precipitation varies from less than 300 [mm yr^{-1}] in the southeast regions to more than 1,500 [mm yr^{-1}] in the northwest ones (Figure 3, right panel) and the 40% of the annual precipitation occurs in winter[6]. The precipitation gradient is also reflected by the mean annual streamflow of the seven river basins. River basins in the northern sector of the Atlantic watershed have a mean annual flow ranging from 10,570 [Hm^3 yr^{-1}] for the Miño-Sil to 12,350 [Hm^3 yr^{-1}] for the Tajo river. Conversely, in the southern sector of the Atlantic watershed the Guadiana and Guadalquivir, rivers have modest mean annual streamflow of 4,039 [Hm^3 yr^{-1}] and 3,780 [Hm^3 yr^{-1}] respectively. In the Mediterranean watershed (i.e., the Jùcar and Ebro basins), the streamflow is generally low except for the Ebro, whose flow is abundant (12,279 [Hm^3 yr^{-1}]) because it is generated in the Cantabrian Range and the Pyrenees. In order to optimize the use of available resources and compensate the differences in the temporal distribution of precipitation, a complex network of dams has been built. Major reservoirs account for a total storage capacity of 56,500 [H m^3][7], that is approximately equal to the mean annual streamflow of the eight main rivers of the peninsula (i.e. 55,850 [Hm^3 yr^{-1}]). As a result, 40% of the natural annual flows in Spain alone is regulated. In Table 1, the power plants installed in the Iberian Peninsula are reported and classified according to the type of technology.

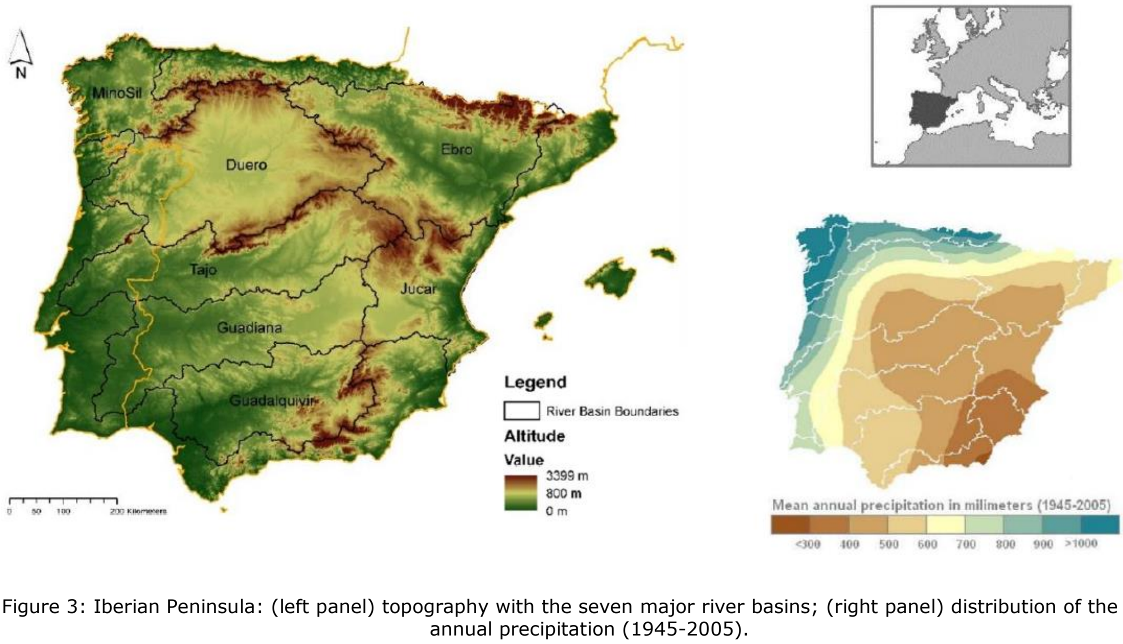

Figure 3: Iberian Peninsula: (left panel) topography with the seven major river basins; (right panel) distribution of the mean annual precipitation (1945-2005).

Table 1. Number of Power plants in the Iberian Peninsula [Source: PRIMES database based on WEPP[8] and EUROSTAT].

	Affected by water availability			Unaffected by water availability[1]		
Power plant	Iberian Peninsula	Spain	Portugal	Iberian Peninsula	Spain	Portugal
Fossil Brown coal/Lignite	1	1	-	-	-	-
Fossil Gas	25	18	7	8	8	-
Fossil Oil	3	1	2	3	3	-
Hard Coal	11	9	2	6	6	-
Hydro mixed pump storage	9	-	9	-	-	-
Hydro pure pump storage	10	3	7	-	-	-
Hydro Run-of-river and pondage	71	60	11	-	-	-
Biomass	3	-	3	-	-	-
Waste	1	-	1	-	-	-
Nuclear	5	5	-	1	1	-
TOT	139	97	42	18	18	-

2.2 Danube region

The Danube River originates in Germany and flows for 2,860 km southeast down to the Black sea. Its drainage area covers about 802,000 km^2 and it is second largest river basin in Europe. This transboundary basin covers 19 countries, with the main river flowing in Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Moldova, Ukraine and Romania (Figure 4). Based on its gradients, this basin can be divided into the upper basin (from Danube source in Germany to Bratislava), the middle basin (from Bratislava to the dams of the Iron Gate Gorge on the border between Serbia and Romania), and the lower basin (Romania and Bulgaria), which includes the Danube Delta.

The climatic conditions of the Danube region are characterized by regular alternating of the seasons of the year typical of the moderate climatic zone of the Northern Hemisphere. Nevertheless, the region shows high variability. For instance, the Upper Danube is subject to the Atlantic influence, the middle Danube Basin is influenced by the Mediterranean, and the eastern territories are affected by a continental climate. Interaction of the mentioned three main effects can trigger floods in the Carpathian basin in any period of the year. The hydrological regime is mainly influenced by precipitations. Average annual precipitation fluctuates within the range of 400 mm in the delta region to above 3000 mm in high mountains. Again, high variability between and within sub-regions is registered (e.g., in upper Danube, precipitation ranges between more than 2000 mm in the Alps and 600 – 700 mm in mid-altitude).

Along the river network flowing within the Danube basin, several power plants have been installed. In 2015, the total electricity production amounted to 98972 GWh (Table 5). Thermal, hydroelectric, and nuclear power plants exploit the freshwater from the Danube river network in their electricity production processes, and contribute to 27.1%, 25.4% and 47.5% of the total electricity, respectively. Concerning the type (Table 2), over the installed 70 power plants, 29 are thermal (fueled with Lignite, Gas, Oil, and Hard Coal), 37 hydroelectric (mixed pump storage, 2, pure pump storage, 3, and run-of-river and pondage, 32), and 4 are nuclear plants.

[1] The Power plants that are included in this section use saline water as coolant in their cooling system, therefore it is assumed that are not affected by the availability of fresh water.

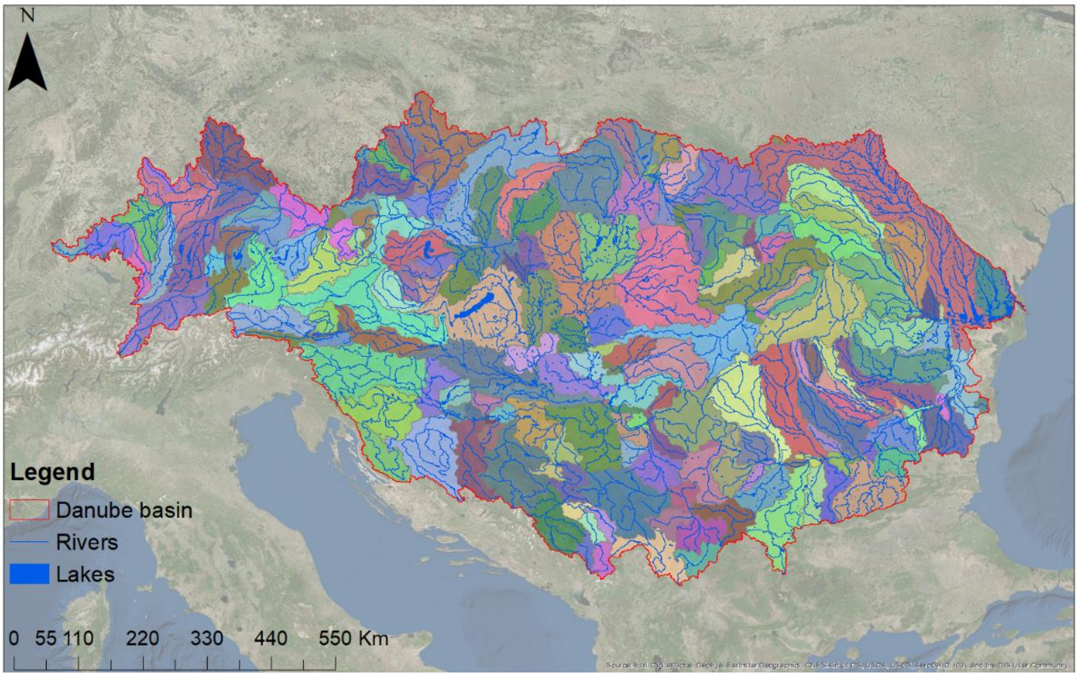

Figure 4. Danube River Basin (red line) and all its natural sub-basins[2] (different colours).

Table 2. Power plants in the Danube River Basin [Source: PRIMES database based on WEPP[8] and EUROSTAT]

Power plant	Danube Basin	Austria	Slovakia	Croatia	Hungary	Bulgaria	Romania
Fossil Brown coal/Lignite	6	1	-	-	-	-	5
Fossil Gas	21	7	2	2	6	-	4
Fossil Oil	1	1	-	-	-	-	-
Hard Coal	1	1	-	-	-	-	-
Hydro mixed pump storage	2	2	-	-	-	-	-
Hydro pure pump storage	3	3	-	-	-	-	-
Hydro Run-of-river	32	17	1	3	-	-	11
Nuclear	4	-	1	-	1	1	1
TOT	70	32	4	5	7	1	21

[2] https://www.eea.europa.eu/

2.3 Alpine region

Figure 5 shows the Alpine regions selected in our analysis. The focus is on Switzerland and Italy, but models will also include Germany, France and Austria, though with lower resolution and less details.

Electricity Generation in Switzerland relies on technologies that have strong connections to the water sector. About 60% of the Swiss electricity is generated by hydropower plants and another 33.5% by nuclear power (which is in a phase-out) that depends on water flow for cooling. The interlink between energy and water is therefore important for Switzerland. The power sector of Switzerland has also a lot of independencies with power sectors in neighbouring EU countries, particularly, Germany and France that will be included in our modelling effort.

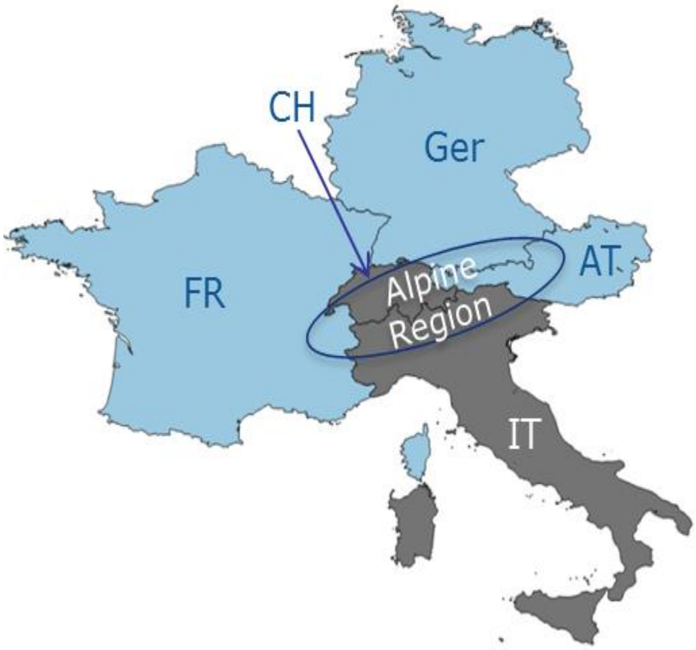

Figure 5. Alpine region. Grey nations are the focus of the analysis; the blue regions will be also modeled at lower resolution to account for the strong interconnection.

Italy, on the other hand, has the highest annual freshwater abstraction in the EU per inhabitant (160 m^3 per inhabitant) and, at the same time, one of the lowest freshwater resources per inhabitant. Italy is the world's 14th largest producer of hydroelectric power, with a total of 50,545 GWh produced in 2014 [9]. Electric energy from hydropower production accounts for about 18% of the national electricity production. While the development of large hydropower schemes is no longer a national priority, the number of active plants has increased of nearly 80% from 2001 to 2014 (Figure 6 , bottom), mostly through small hydro plants (e.g. run-of-the-river facilities), reaching 3,432 active plants in 2014.

Amongst those plants only 302 had more than 10 MW of power capacity in 2014, but nevertheless they constituted almost 83% of the total installed hydropower capacity at the national level. The gross maximum capacity achieved around 18,531 MW in 2015 (Figure 6, top). Hydropower production is mostly concentrated in the northern part of the country (Figure 7), where abundant snow accumulation and steep slopes created the perfect requisites for hydropower development in the past century across most of the Alps. For instance, the hydropower plants located in north Lombardy, Piedmont and Trentino-Alto Adige contribute for almost 60% of the total hydropower capacity in Italy. Most of the hydropower plants with large installed capacity (>10 MW) have been operated by three companies, namely Enel, Edison, and A2A Group (A2A and Edipower).

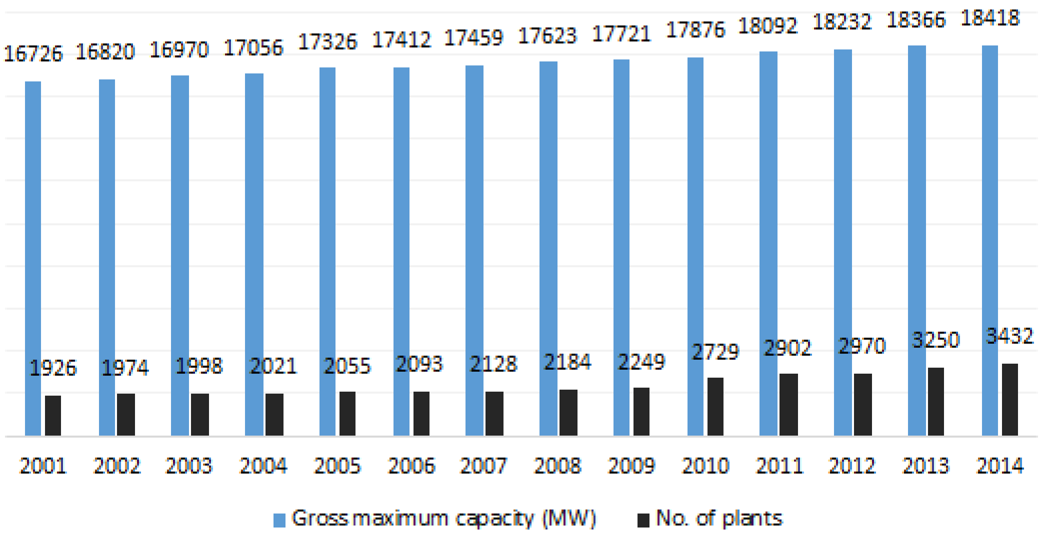

Figure 6: Growth of gross maximum capacity (blue bars; [9]) and number of hydropower plants (black bars; [9]).

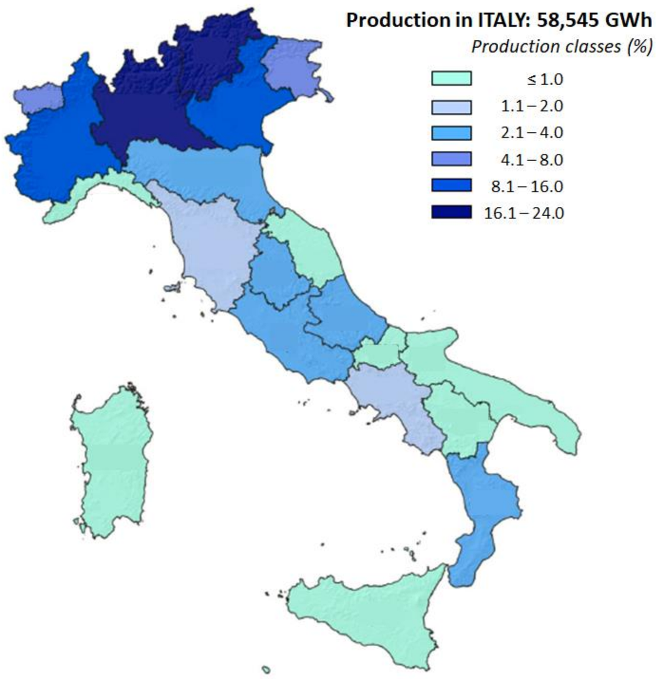

Figure 7: Hydroelectric energy production in Italy for 2014 [9].

2.4 *Adda River basin*

The Adda River is the fourth longest Italian river and a tributary of the Po River. It flows into Lake Como, a regulated lake with an active storage capacity of 254 Mm^3 draining a 4,550 km^2 catchment (Figure 8). The hydro-meteorological regime of the basin is typical of sub-alpine regions, characterized by dry periods in winter and summer, and peaks in late spring and autumn fed by snowmelt and rainfall, respectively. The catchment includes 47 power plants (see Table 3), for an associated installed power capacity of about 2,000 MW, and a cumulated storage capacity of 545 Mm^3 (i.e., two times larger than the active storage of the lake).

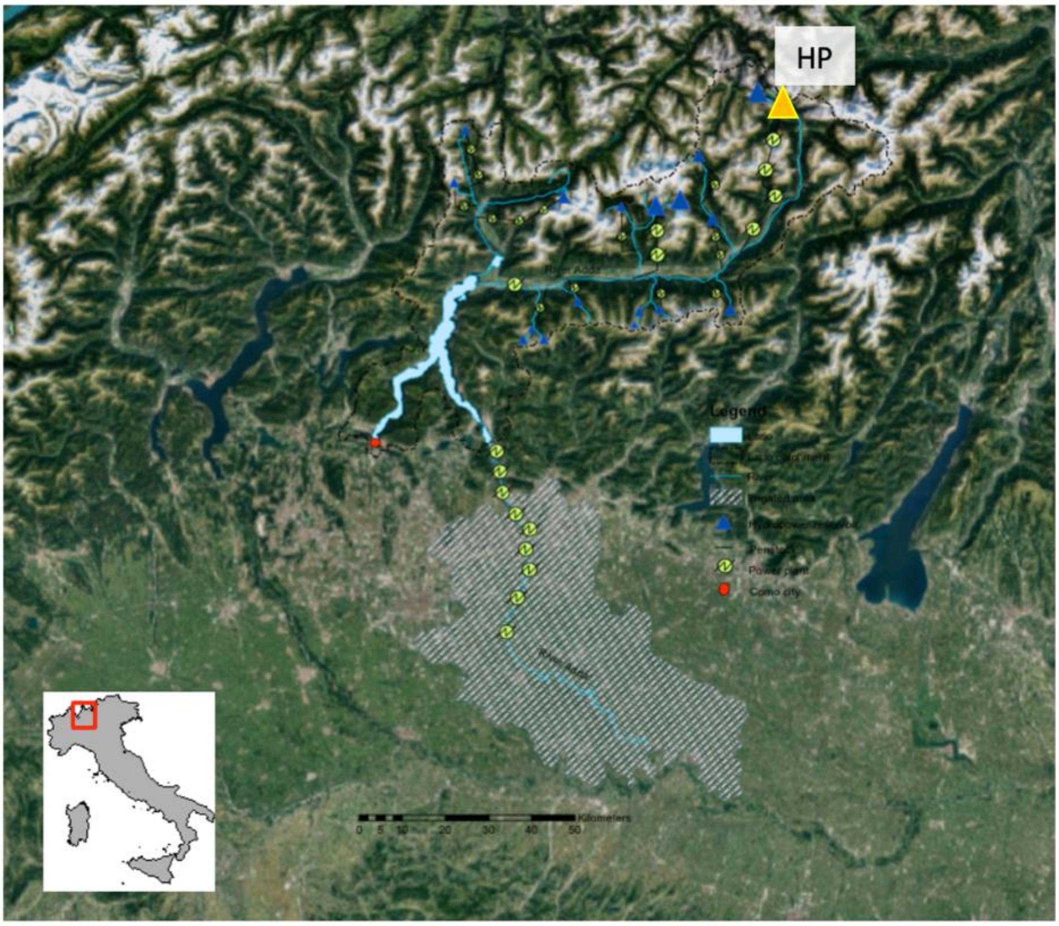

Figure 8: Map of the Adda River basin, with the modelled HP plant in yellow (HP).

Table 3: Hydropower plants in the Adda River basin.

Hydropower Plant	Company	installed capacity (MW)
Premadio	A2A	245
Grosio	A2A	431
Lovero	A2A	57.9
Stazzona	A2A	46.4
Lanzada	Enel	13.8
Gerola Alta	Enel	188
Venina	Edison	67
Belviso	Edison	66
Ganda	Edison	66

Isolato Spluga	Edipower	42.8
San Bernardo	Edipower	34.2
Mese	Edipower	172.6
Palù	Repower	10
Cavaglia	Repower	7
Robbia	Repower	27
Campocologno	Repower	45
Lobbia	EWZ	95
Braulio	A2A	19
Grosotto e Boscaccia	A2A	15.2
Gravedona	Edipower	12.7
Cremia	Edipower	0.5
Gordona	Edipower	14.6
Prata	Edipower	3.3
Chiavenna	Edipower	66.9
Prestone	Edipower	23.5
San Pietro Sovera	Edipower	2.6
Rescia	Edipower	0.5
Madesimo	Edipower	16.2
Armisa	Edison	11
Vedello	Edison	33
Zappello	Edison	11
Publino	Edison	2
Ardenno	Enel	57
Campo Moro	Enel	36
Boffetto	Enel green power	0.896
Bertini	Edison	11
Esterle	Edison	23
Semenza	Edison	7
Vaprio d'Adda	Italgen	20.9
Centrale Rusca (Cassano d'Adda)	Podini Holding	6.5
centrale 20.1 DMV/Italcementi	Eneco	0.857
Pizzighettone	Edison	4.3
Maleo	Edison	3
Taccani	Enel	10.5
Centrale Legler (Capriate)	Adda Energia	0.858

2.5 *Status quo of the regions in 2015*

In the following tables data about the current electricity system and water infrastructure are reported for each modelled region. Generation, share of generation in percentage, water consumption and withdrawal are shown for each electricity source. Electricity consumption and generation are reported for each water infrastructure system segment.

Table 4. Electricity System of the Iberian Peninsula based on PRIMES results for 2015, EC Reference Scenario 2016[10].

Generation Type	Current Electricity System of Iberian Peninsula (2015)			
	Electricity Generation (GWh)	Share (%)	Water Consumption (hm^3/year)	Water Withdrawal (hm^3/year)
Hard Coal	62,031	19.8%	37	5,607
Natural Gas	60,265	19.2%	34	1,403
Nuclear	54,932	17.5%	104	4,055
Oil	5,541	1.8%	2	568
Hydropower	45,337	14.5%	0	764
Biomass	2,171	0.7%	0	14
Fossil Brown coal/Lignite	4,231	1.4%	8	9
Other (Solar, Wind, Geother.)	78,567	25.1%	15	22
TOT	313,075	100%	185	12,442

Table 5. Electricity System of the Danube River Basin based on PRIMES results for 2015, EC Reference Scenario 2016[10].

Generation Type	Current Electricity System of Danube River Basin (2015)			
	Electricity Generation (GWh)	Share (%)	Water Consumption (hm^3/year)	Water Withdrawal (hm^3/year)
Hard Coal	1,747	1.8%	1	179
Natural Gas	11,893	12.0%	6	445
Nuclear	46,977	47.5%	59	6,719
Oil	71	0%	0	7
Hydropower	25,167	25.4%	0	374
Fossil Brown coal/Lignite	13,117	13.3%	34	34
TOT	98,972	100%	100	7,758

Table 6. Water Infrastructure System of the Iberian Peninsula based on PRIMES results for 2015, EC Reference Scenario 2016[10].

Water Infrastructure System Segment	Current Water Infrastructure System of Iberian Peninsula (2015)	
	Electricity Consumption (GWh)	Electricity Generation (GWh)
Conveyance	0	0
Treatment	0	0
Distribution	0	0
Irrigation	2,741	0
Hydropower	0	41,731
Pumped Hydropower Storage	4,970	3,606
TOT	7,711	45,337

Table 7. Water Infrastructure System of the Danube River Basin based on PRIMES results for 2015, EC Reference Scenario 2016[10].

Water Infrastructure System Segment	Current Water Infrastructure System of Danube River Basin (2015)	
	Electricity Consumption (GWh)	Electricity Generation (GWh)
Conveyance	0	0
Treatment	0	0
Distribution	0	0
Irrigation	1,682	0
Hydropower	0	21,972
Pumped Hydropower Storage	4,563	3,195
TOT	6,245	25,167

Table 8. Electricity System of Switzerland and Italy (2015)[10] [11].

Generation Type	Current Electricity System of Switzerland (2015)			
	Electricity Generation (GWh)	Share (%)	Water Consumption (hm^3/year)	Water Withdrawal (hm^3/year)
Coal	45,400	13.0%	1.1	4.6
Natural Gas	113,000	32.5%	174.7	5,697.6
Nuclear	22,100	6.3%	61.9	3,369.5
Oil	13,400	3.8%	20.7	674.6
Hydropower	86,000	24.7%	0.0	0.0
Solar	22,900	6.6%	1.2	1.2
Wind	14,800	4.3%	0.0	0.0
Other	30,500	8.8%	0.0	1,535.3
Total	348,100	100.0%	259.5	11,282.8

Table 9. Water Infrastructure System of Switzerland (2015)[11].

Water Infrastructure System Segment	Current Water Infrastructure System of Switzerland (2015)	
	Electricity Consumption (GWh)	Electricity Generation (GWh)
Conveyance, Treatment, Distribution of drinking Water	400	-
Distribution	-	-
Irrigation	-	-
Hydropower (run of river)	0	16,600
Hydropower Storage (with Pumped Storage)	2,300	22,900
Wastewater Treatment	500	-
Water heating	2,500	-
TOT	5,700	39,500

3 Methodology

In order to quantify the effects of changes in water availability and the effect on power generation, the Hydrologiska Byrans Vattenbalansavdelning (HBV) hydrological model [12][13][14] was soft-integrated with two power system models –PRIMES-IEM and ENTIGRIS- used in unit commitment[3] mode. For the detailed river basin analysis, the hydrological model TOPKAPI-ETH [15][16] was used in a feedback loop configuration together with the ENTIGRIS model.

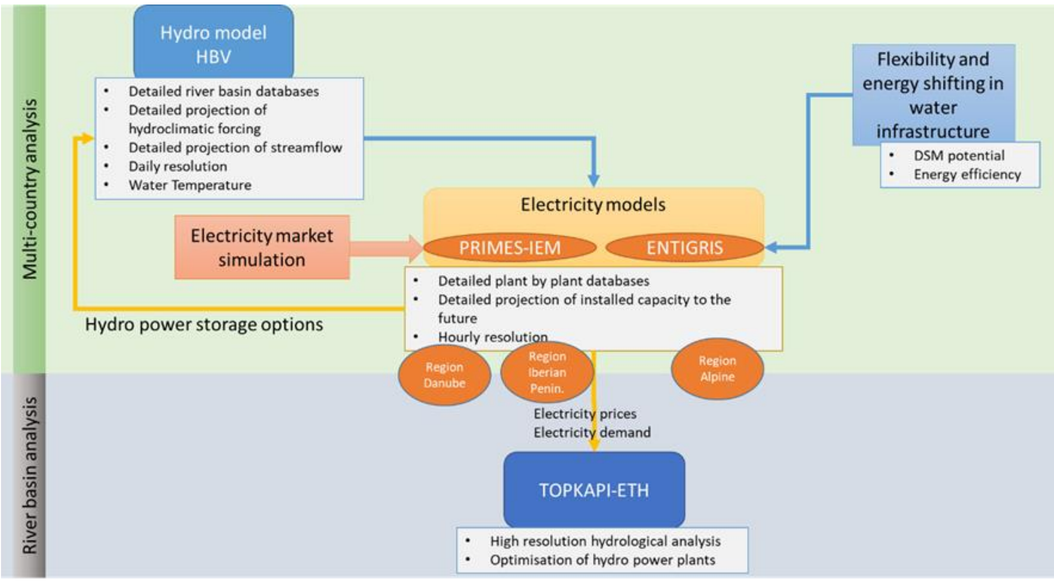

Figure 9 : Overview of the overall analysis

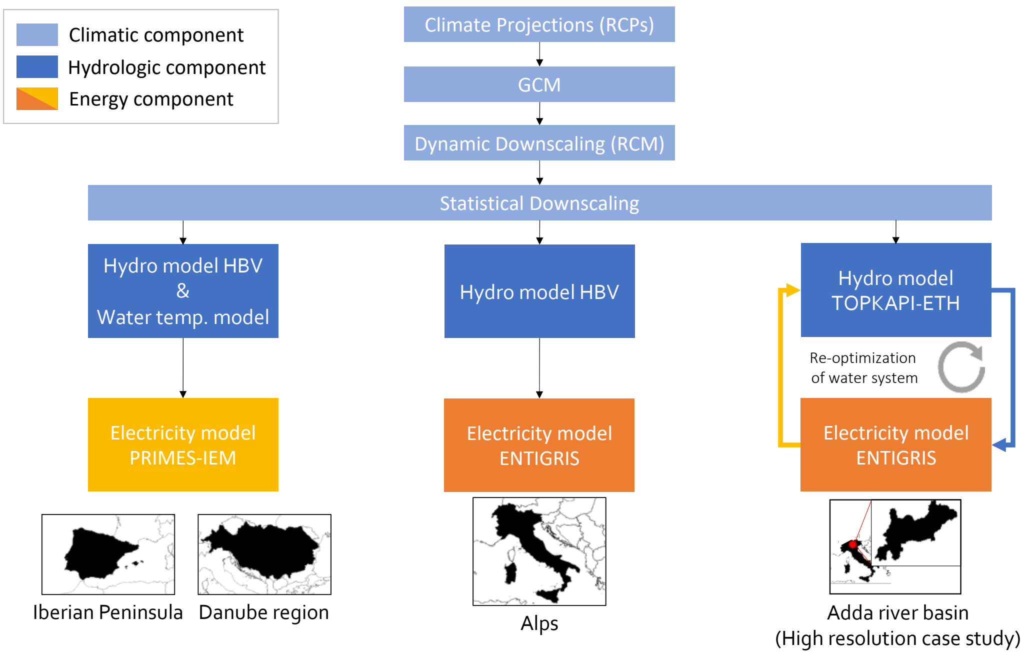

Figure 10 : Methodological scheme.

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[3] The Unit commitment problem is the mathematical optimisation of coordination of electrical generators to match demand and supply or maximise revenues of generators

The three main approaches are reported in Figure 10. Climate projections are the inputs of the hydrological models that compute streamflow projections (and water temperature if needed) used to constrain the respective energy model for each modelled region.

Climate projections processing

The Representative Concentration Pathways [17] (RCPs) published in the last IPCC (Intergovernmental Panel on Climate Change – United Nations) report [18] are used to compute projections of hydroclimatic variables by GCM [19] (General Circulation Models). These models have a very small resolution and therefore their output is used as a boundary condition to simulate RCM [20] (Regional Climate Models) and produce results at a smaller scale. This procedure is called dynamical downscaling as it involves running a climatic model at a higher resolution, accounting for dynamic phenomena that take place at a lower scale not modelled in the GCM. Yet, the precision obtained with this procedure is not enough for several specific applications, as for example providing the precipitation and the air temperature over basins with a surface of few square kilometers. In order to improve the quality of the considered climate projections for assessing the impacts of climate change at the local scale, we applied a statistical downscaling technique, i.e. quantile mapping [21][22].

Statistical downscaling: quantile mapping

In order to implement this technique, observational data at the local scale are needed to correct the output of RCM simulations over the historical control period (i.e. the period for which observational data are available). This bias correction relies on a statistical correction function based on the cumulative distribution of both simulated and observational data.

The simple idea behind the quantile mapping procedure is to apply the same correction function used to adjust the bias in the past to future projections of hydroclimatic variables. Under this assumption of stationary model bias, this procedure yields good results at a low computational cost [23]. The methodology is synthetically shown in Figure 11.

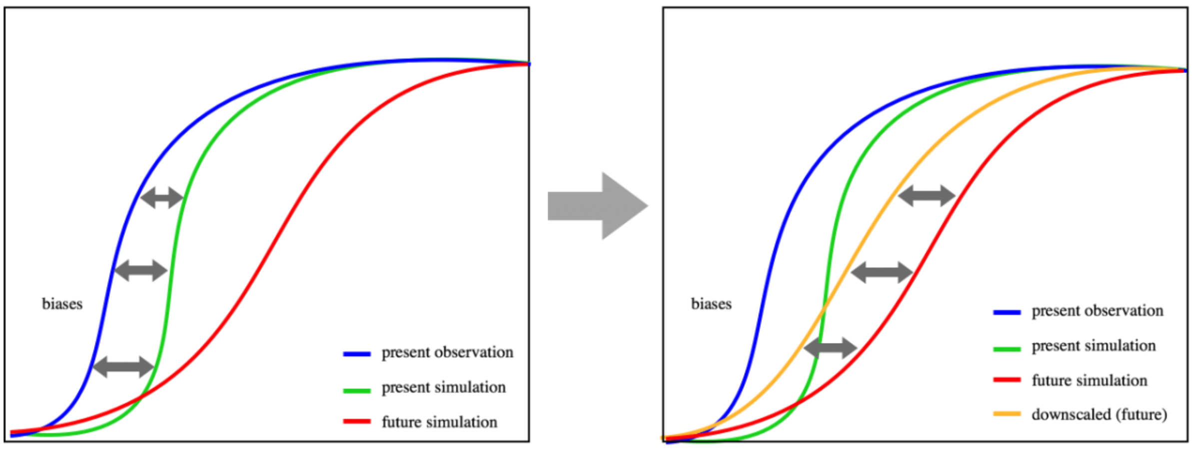

Figure 11: Quantile mapping method. Retrived online at https://rcmes.jpl.nasa.gov/content/statistical-downscaling.

3.1 The Hydrologiska Byrans Vattenbalansavdelning model (HBV)

The HBV model is a lumped, conceptual rainfall-runoff model originally developed for operational flood forecasting in Sweden. The model is composed by a cascade of four storage units and simulates the soil water balance and subsequent runoff produced by rainfall, snowmelt, and evapotranspiration.

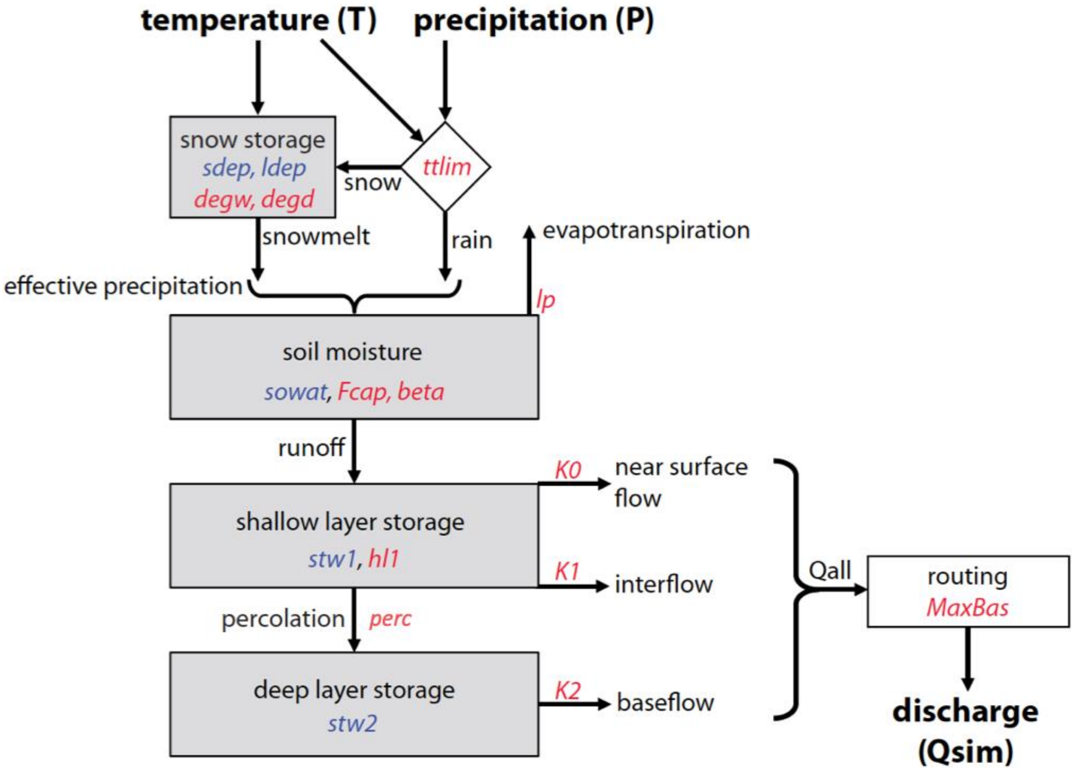

Figure 12: The HBV model structure.

In Figure 12, the main variables and parameters of the HBV model are reported. The inputs are temperature and precipitation in bold on the top of the diagram, while the output is the discharge, in the bottom-right corner. The state variables of the model – in blue - are the solid snow storage, liquid snow storage, soil water content, shallow layer storage, and deep layer storage. The model is dependent upon twelve parameters, highlighted in red, which regulate the flow between the different storage units and the outflows, i.e. evapotranspiration and discharge. A proper tuning of these parameters is fundamental to accurately model the flow measured at the outlet of the modelled basin.

These parameters allow the model to be quite flexible. This, together with its ease of use, are the reasons behind his large success and applications in many different basins around the world. We implemented an open-source version of the HBV model[4], including an interface to couple it with a library of Multi-Objective Evolutionary Algorithms to perform an automatic calibration of the model parameters with respect to observational data.

[4] The HBV model is available at: http://mxgiuliani00.github.io/hbv/

3.2 *Air to water temperature: logistic regression model*

In order to compute to estimate water temperature at the different locations of interest the local air temperature (derived from dynamical downscaling of climate projection) has been obtained through a simple regression method [24]. It is based on the logistic equation, i.e.:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}}$$

Where:

- T_a is the air temperature [°C]
- T_s is the stream temperature [°C]
- μ, α, γ and β are empirical parameters

The parameters and the logistic regression functions are shown in Figure 13. The empirical parameters for the Duero [3] have been extended to all the basins in Spain. The parameters used in the Danube region are available in the literature [25]. Even if the methodology adopted was originally developed for weekly data [24], we've been using it with a daily step, as common practice in the literature [25].

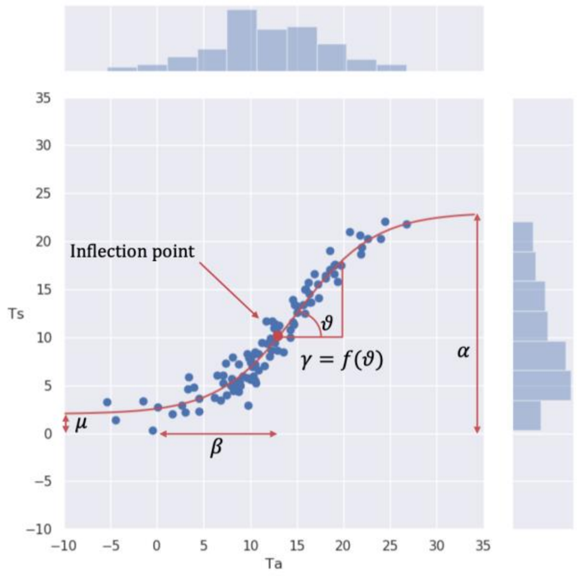

Figure 13: Logistic regression model.

3.3 *PRIMES-IEM*

The PRIMES-IEM model [26] is part of the PRIMES modelling suite, which is a modular full energy system model. The PRIMES energy system model has been used for the preparation of the EU Baseline/Reference scenario since the 1990's and also prepared its latest version of EU Reference scenario in 2016 [10]. Moreover, the PRIMES model has been used in the preparation of the so-called EUCO scenarios [27] for the 2030 Clean Energy for all Europeans package[5] and even more recently for the preparation of the Mid-Century strategy, the Clean Planet for all vision[6].

The PRIMES-IEM model is a satellite model to analyse in depth the Internal Energy Market (IEM) and consists of a number of interlinked modelling tools to study the full functioning of the internal market for electricity; it has been used for the preparation of the Market Design Initiative [28]. The PRIMES-IEM model uses the projections based on the full PRIMES energy system model and simulates the sequence of the European markets and system operation hourly. The model therefore includes a day-ahead market simulator, a unit commitment simulator, an intra-day and balancing market simulator, as well as a reserve and ancillary market simulator.

The PRIMES-IEM covers all EU 28 Member States individually. It also represents Norway, Switzerland and the Western Balkan countries, in an aggregated manner, in order to account for the exchanges of energy between the EU and these countries. PRIMES-IEM includes the representation of the interconnection network, using the flow-based approach

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[5] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

[6] https://ec.europa.eu/clima/policies/strategies/2050_en#tab-0-0

and runs all countries simultaneously[7]. The assumptions about the grid change over time, reflecting an exogenously assumed grid investment plan. Existing power capacity of lines and new constructions are based on ENTSO-E data and the TYNDP[8].

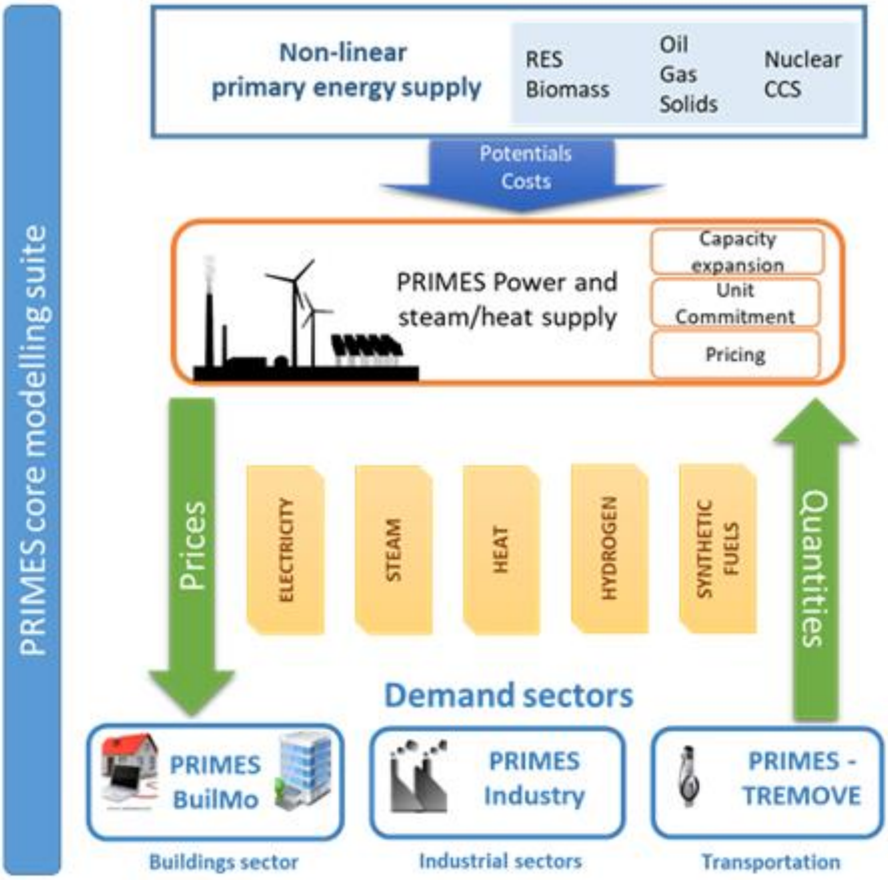
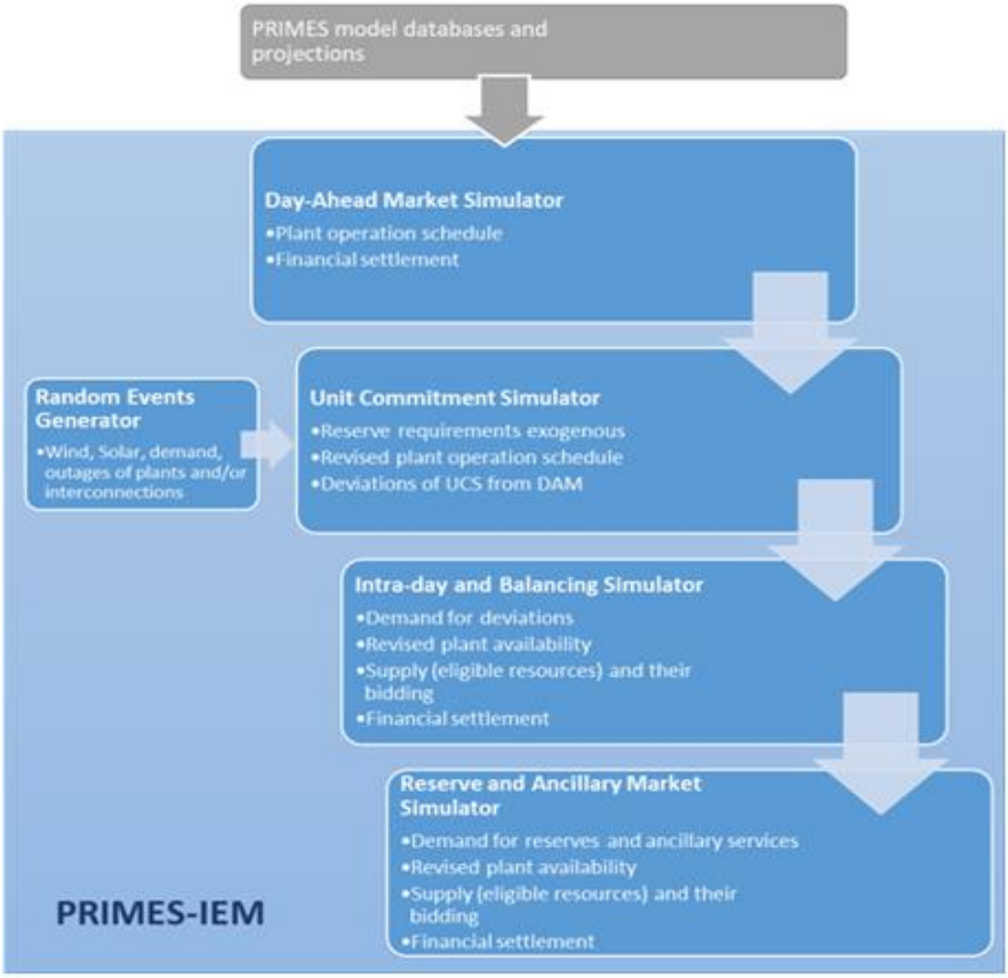


Figure 14: PRIMES structure

[7] For the purpose of this study, two regions were studied using PRIMES-IEM, the Iberian Peninsula and the Danube Region. Thus, these two regions were simulated separately, assuming that their electricity exchanges with the rest of the countries remain constant across scenarios and are based in the full PRIMES results.

[8] https://www.entsoe.eu/publications/tyndp/tyndp-2016/

Figure 15. PRIMES-IEM structure



For the purpose of this study the unit commitment simulator of PRIMES-IEM was used, aiming at simulating the operation of the Iberian and Danube power system. The unit commitment simulator takes the projections of the main PRIMES model as input data (see Figure 16). The inputs from the main PRIMES model projections include:

- Hourly load demand, power plant capacities, net imports with countries outside the studied regions, capacity of transmission lines and net transfer values (NTC)
- Fuel prices, ETS carbon prices, taxes, etc.
- RES generation, however the simulator determines endogenously whether RES curtailment is needed+
- Potential of hydro production
- Heat or steam serving obligations of the CHP units, whose main product is heat or steam rather than electricity (industrial CHP and small CHP units exclusively used for steam and heat)
- Other restrictions derived from specific policies, e.g. operation restriction on old plants, renewable production obligations and if applicable, support schemes of renewables, biomass and CHP

The model includes the full PRIMES database of power plants, which includes all power plants in Europe. The power plant database includes disaggregated technical and economic data for each plant, in order to be able to represent the cyclical operation of plants and possible start-ups/shut-downs. The database also includes detailed data on the technical possibilities of plants to provide ancillary services. The model has hourly resolution, it includes all technical constraints to the power plants (technical minimum, minimum up and down time, ramping rates etc.) and has a detailed representation of system requirements, including electricity equilibrium and several reserve types. The ancillary services covered include the Frequency Containment Reserve (FCR), Automatic and Manual Frequency Restoration Reserve and Replacement Reserve. The model output presents the commitment schedule, the power generation level and the contribution to each type of ancillary services on a plant by plant resolution for thermal power plants. The schedule of RES generation power plants is also projected by plant type.

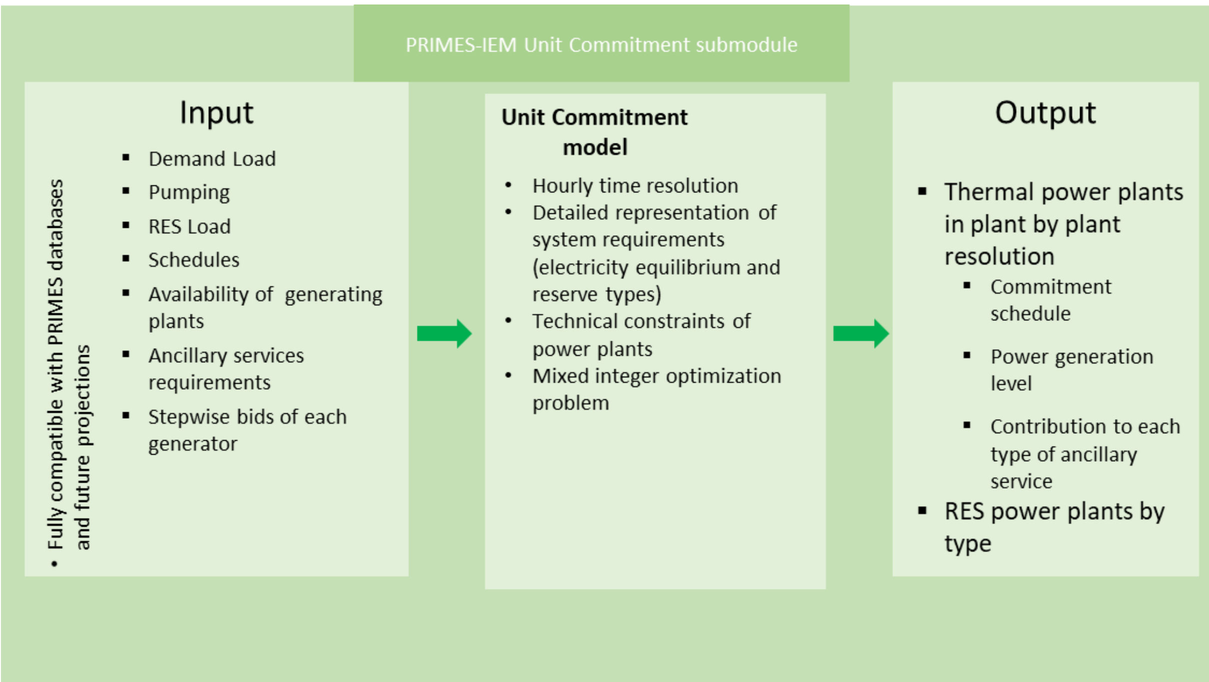


Figure 16: Schematic overview of the PRIMES-IEM Unit Commitment simulator

In order to study the impact of water availability on power generation, the additional information deriving from the hydrological model was incorporated in the PRIMES_IEM model as additional parameters: the projected changes in streamflow of rivers are transformed into a changed potential in hydropower generation for each diverging hydro-scenario, and the projected changes in water temperature are transformed into an additional constraint to thermal and nuclear power plant operation.

PRIMES-IEM: key model adaptations

Water usage coefficients of power plants

Different types of power plants, present different needs for cooling water (water withdrawal and-or water consumption). Complete data about water consumption and water withdrawal coefficients per plant were taken from J.Macknick et all (2012) [29] and are shown in Table 10. When studying the water usage of power generation, it is important to distinguish between water withdrawal and water consumption. Water withdrawal represents the total water withdrawn from a source and returned, while water consumption represent the amount of water withdrawal that is not returned to the source[30]. These coefficients when multiplied with the amount of energy generated from the respective power plant enable us to estimate the water withdrawal and water consumption that each particular power plant presents in the absence of power plant specific data, which was not found.

Table 10: Water withdrawal and water consumption coefficients per plant type [29].

		Water Consumption (m^3/MWh)		Water Withdrawal (m^3/MWh)	
Fuel type	**Technology**	**Closed Loop**	**Once Through**	**Closed Loop**	**Once Through**
Nuclear	Generic	2.544	1.018	4.168	167.883
Fossil gas	Combined cycle	0.776	0.379	0.965	43.078
	Steam	3.127	0.908	4.554	132.489
	Combined cycle with CCS	1.488	0.726	1.915	85.480
Hard Coal	Generic	2.601	0.946	3.804	137.600
	Subcritical	1.813	0.428	2.222	102.539
	Supercritical	1.866	0.390	2.400	85.512
	IGCC	1.438	0.428	1.488	102.539
	Subcritical with CCS	3.486	0.822	5.031	232.154
	Supercritical with CCS	3.202	0.669	4.342	154.705
	IGCC with CCS	2.078	0.618	2.430	167.507
Biomass	-	2.093	1.136	3.324	132.489
Lignite	-	2.601	0.946	2.601	137.600
Fossil oil	-	1.813	0.428	2.222	102.539
Hydro	-	-	-	-	17.000
CSP (solar-thermal)	-	3.430	-	4.995	-

Thermal and Nuclear power plants: Cooling system types

As shown in Table 10 different types of cooling systems present different needs for cooling water for the same type of power plant. There are three main types of cooling systems[31]:

- Once-through systems withdraw water from nearby sources, circulate it through pipes to absorb heat from the steam in the condenser, and discharge the water to the local source at a higher temperature

- Wet-recirculating or closed-loop systems reuse the cooling water instead of discharging it back to the water source. These systems use cooling towers to expose water to ambient air and drop its temperature. A part of the water evaporates and the rest is reused for cooling. Wet-recirculating systems have lower water withdrawal than once-through systems, as they only replace any water lost through evaporation, but present higher water consumption

- Dry cooling relies on air, rather than water, as the primary coolant medium to transfer heat through a surface that separates the circulating cooling fluid from ambient air

The Iberian Peninsula's thermoelectric power plants fleet for 2015 consists of 35% once-through fresh water cooling system, 38% wet recirculating cooling system and the rest use once-through saline water or dry cooling system.

As far as the Danube Region is concerned, 38% of the thermoelectric plant fleet is equipped with wet-recirculating cooling system, while the remaining 62% uses once-through cooling system.

Dry cooling systems are less efficient from a thermodynamic point of view and are therefore implemented when there is a lack of water resources. Once-through and closed-loop systems are similar regarding thermodynamics, but closed loop system significantly reduce the environmental impact on the water systems due to the significant reduction of water withdrawal (over 90%), therefore reducing impacts on the water eco-systems. Once-through systems are simpler to construct present low capital and operating cost [32] and have been installed in older power plants when environmental impacts were not the highest priority.

European Legislation affecting power plant operation

In the European there is a very large range of legislation which influences the operation of power plants ranging from security, environmental legislation related to pollutants, the emission trading schemes etc.

Specific European legislation regulates water usage/discharge which effects the operation of thermal and nuclear power plants: the Freshwater Fish Directive (2006/44/EC) [33]: firstly, according to the legislation the temperature - measured downstream of a point of thermal discharge - shall not to exceed the unaffected water temperature by more than 3°C for cyprinid waters (1.5°C for salmonid waters); secondly, thermal discharges must not cause the temperature downstream of the point of thermal discharge, after mixing with the original water body, to exceed 28°C for cyprinid waters (21.5°C for salmonid waters). Furthermore, based on the European Environmental Agency [34], the temperature of water at the discharge point should not exceed 30°C. For the areas under consideration in this study, all waters are assumed cyprinid due to their geographic location.

In order to study the behaviour of thermal and nuclear power plants under constrained water availability, a methodology was developed based on a model described from Forster and Lilliestam (2011) [35], which aims to examine the effects of climate change to thermoelectric generation, focusing on power plants equipped with once-though cooling system, since power plants equipped with wet-recirculating cooling system have very little interaction with the water bodies.

As in the original model, energy P denotes the energy supplied to the power plant. A water volume v is constantly withdrawn from the water body, which exhibits stream flow V, for cooling the power plant during the electricity production process. The unaffected withdrawn water has the temperature T_0. P_{el} —the electricity output—and all other non-cooling energy outputs are removed from the power plant via the power grid, by exhaust fumes (if applicable) and by own consumption. The discharged cooling water has a temperature T_1>T_0 (if P_{el} >0). The water temperature at discharge point is Tm. ɑ describes the efficiency factor of the power plant. The cooling factor β is the sum of ɑ, the percentage of energy used for own consumption and the energy lost through flue gases (only applicable for combustion power plants).

Table 11: Model Variables and Parameters

P	Primary energy input (MW)
P_{el}	Other, non-cooling energy output
P_w	Energy which is cooled away (MW)
V	River stream flow at the location of the power plant (m^3/s)
v	Withdrawn water (m^3/s)
f	Water withdrawal factor (m^3/s), based on the power plant type and cooling system technology
ɑ	Efficiency factor
β	Cooling factor
T_0	Temperature of unaffected water
T_1	Temperature of discharged water
T_m	Mixed temperature of water downstream of the power plant
C_v	Specific heat recovery of water (MJ/kg K)
ρ	Water density (kg/m3)

$$\boldsymbol{P_{el} = P\beta = P - P_w} \qquad (1)$$

Where $\boldsymbol{v = P_{el}\, f}$ (2)

$$\boldsymbol{P_w = v(T_1 - T_0)\rho C_v} \qquad (3)$$

Thus, one can write:

$$\boldsymbol{P_{el} = \frac{P_{el}}{\beta} - v(T_1 - T_0)\rho C_v} \qquad (4)$$

Which in turn can be formalized into the following production function:

$$\boldsymbol{P_{el} = \frac{-v(T_1 - T_0)\rho C_v}{1-\frac{1}{\beta}}} \qquad (5)$$

The mixed temperature of the water body at the mixing point can be expressed as:

$$T_m = \frac{vT_1 + (V-v)T_0}{V} \qquad (6)$$

Based on the legislation discussed above we conclude to the below water constraints:

1. *Temperature at the discharge point*

$$T_1 = \frac{(1-\frac{1}{\beta})P_{el}}{-v\,\rho\,C_v} + T_0 \quad \leq 30°C \qquad (7)$$

2. *Difference of temperature (downstream-upstream)*

$$\Delta T = T_m - T_0 = -\frac{(1-\frac{1}{\beta})P_{el}}{V\,\rho\,C_v} \leq 3°C \; (8)$$

3. *Water availability*

$$v \leq V \qquad (9)$$

4. *Mixed temperature*

$$T_m = \frac{vT_1 + (V-v)T_0}{V} \leq 28°C \qquad (10)$$

Power plants, equipped with wet-recirculating cooling system have very little interaction with the water bodies since they only replace the water evaporating; thus, no water constraints on the discharge point are applied to these plants. Consequently, this type of power plants is only affected by the water availability constraint

It is assumed that if the temperature of unaffected water (T_0) is higher than the environmental limit of 28℃ then all power plants will be forced to completely shut down independently of the type of cooling system.

For the locations of power plants studied here, the water availability constraint is never binding.

PRIMES-IEM adaptations for Hydro power plants

For the quantification of the impact of effects of climate conditions on the hydropower potential, we used a method that has already been proposed by Lehner *et al.* (2005) [36] and used by Van Vliet et al. (2012)[25]. This approach enabled us to calculate the decreased hydropower potential directly from the datasets of the decreased water availability provided by the HBV hydrological model. Lehner *et al.* (2005) concluded that this particular approach is a good indicator for estimating the relative change in actual hydropower potential.

PRIMES-IEM Key Assumptions for this study

The study focused on the interactions between water availability and power generation. A number of assumptions had to be taken including:

- Based on the World Electric Power Plants Database [37] the majority of new power plants commissioned in the last 20 years in the Iberian Peninsula and the Danube River Basin region use wet-recirculating cooling system. Therefore, in the context of this study, it is assumed that future greenfield investments use wet-recirculating cooling system, while future brownfield investments use the cooling system of the existing site.

- All rivers, in the regions analysed, are assumed to have cyprinid waters.

- Power plants that use saline water in their cooling system were excluded from this study; their water availability is assumed to remain unchanged and temperature limitations do not apply.

- Power plants that are equipped with dry cooling system are excluded from the study since they are not affected by the availability of the water.

- The Iberian Peninsula includes all power plants of the electricity supply for Spain and Portugal; the Danube River Basin analysis includes only power plants whose cooling system lies on the Danube or its tributaries and does not use national boundaries for the analysis.

- Within this study, we consider that each of the two examined regions (Iberian Peninsula and Danube River Basin) has fixed import/exports with neighbouring regions and therefore has to deal with the problems deriving from water availability on its own. The import/exports are fixed at the level used within the EUCO Reference used within this study which were calculated for the entire EU (plus Norway and Switzerland). Within each region, the cross-border trade is endogenously calculated within the PRIMES – IEM model; thus, it is limited only by the physical transfer limits of lines and Kirchhoff's laws. In the scenarios analysed, e.g. a year of water scarcity, water availability will most probably change also in neighbouring countries/areas and not only the regions, considered in this study. Thus, it would be misleading to assume that the examined regions in this study could rely on limitless electricity flows from neighbouring countries.

- This study focused on the operational phase of power generation, thus water usage in other stages of the life cycle was excluded.

Interaction PRIMES-IEM and HBV model

Water temperature and streamflow are produced at the power plant scale of interest for the electricity model PRIMES-IEM. For each power plant, the associated hydrological basin has been delineated and used in both hydroclimatic variables processing and daily streamflow computation.

The streamflow projections deriving from HBV have been used to constrain hydropower production of hydropower plants in the electricity model.

Both streamflow projections from HBV and the water temperature obtained with the logistic regression model have been used to check whether the cooling efficiency of thermonuclear power plants will be affected in the future. As the water requirements for cooling in many plants are not large in volume, water availability is not really relevant in this case. On the other hand, this water use can significantly be affected by water temperature. Therefore, only the later has been used to constrain the cooling efficiency of the thermonuclear plants.

3.4 ENTIGRIS

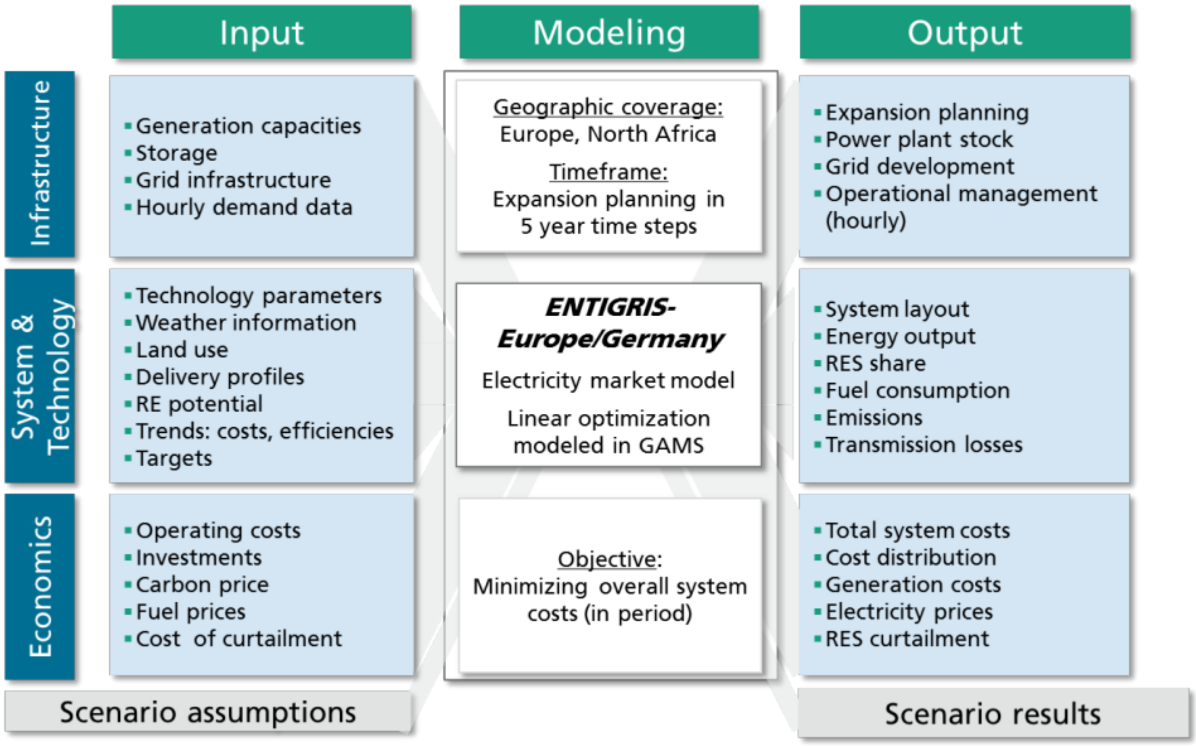


Figure 17: Schematic overview of the ENTIGRIS optimization model

ENTIGRIS is an expansion and unit-commitment optimization model for the power sector. Currently, the model has been used in Europe, North Africa and Middle East. It was applied to specific country analysis, e.g. Germany, Greece, Morocco, Egypt, South Africa. The model covers expansion planning of power generation technologies including renewable energy sources and transmission capacities (net transfer capacity - NTC) over the future. The problem is implemented as a linear program which minimizes total system costs consisting of expenditures for construction and operation of the power system. The model also integrates the existing conventional power plant system in the analysis, as well as high-resolution simulation of renewable energy generation. The model can include technical and economic constraints as well as RES targets or CO_2 reduction targets for specific years. The relation between model input and model output is displayed in Figure 17.

In this study ENTIGRIS is used as a unit commitment model, with an hourly resolution and for 8760 hours. Power plants outside of Switzerland and non-hydro power plants in Switzerland are aggregated. Transmission constraints between the countries are included as well.

ENTIGRIS: key model adaptations

The representation of hydro power in ENTIGRIS had to be expanded to allow for the high level of detail and to implement the cascade effect that the different power plants have on each other. Previously, hydropower plants were aggregated and deployed with a pre-calculated energy availability for their energy production. The hydropower plants are now part of a network of water flows. The water flow decides if a power plant can produce energy or not. The following picture shows the schematics of the new modelling approach.

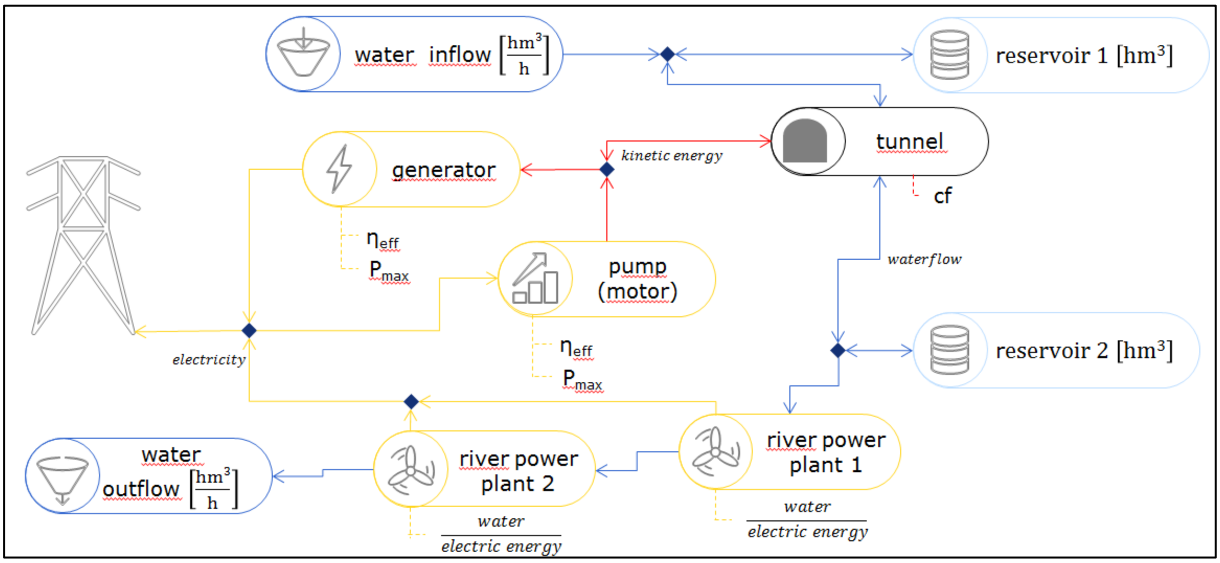


Figure 18: Schematic overview of the new ENTIGRIS water modelling

The hydro modelling consists of 7 key elements.

Water inflow: The water inflow is the streamflow of water that is usable for the energy system. The streamflow is calculated using the daily streamflow of the HBV model and the yearly water flow of the power plant. The yearly water flow for each power plant is calculated using data from the hydropower plants statistics by the Swiss Federal Office of Energy (SFOE) [38]. The yearly water flow was calculated as follows:

$$\frac{QTurbine\left[\frac{m^3}{sec}\right] * 3600\left[\frac{sec}{h}\right]}{PTurbine[MW]} * ETurbine\left[\frac{MWh}{year}\right] = QWaterflow\left[\frac{m^3}{year}\right]$$

Since the hydro power plants are part of a hydro network, the water flow has to be separated in two parts. The first part is the natural inflow. That is the inflow that comes from outside of the hydro network that is mapped in the model. This is for example water that comes from tributaries or if a power plant is the first power plant in a cascade of power plants and receives its water from a river or glacier. The second part is the water flow that is already in the mapped hydro network. For example, from a reservoir or another power plant that is upstream from the considered power plant. If the natural inflow is greater than zero for a power plant a water inflow is placed in front of the power plant and the water inflow is calculated by the time series of the basin from the HBV Model and the yearly water volume that comes from natural inflow.

Reservoir: A reservoir is depicted as a simple storage. The difference is that not energy but water is stored. The storage regulates the inflow and outflow of water in the reservoir.

Tunnel: The tunnel part of the model is used to calculate the kinetic energy of the water that flows through the tunnel. The conversion factor is calculated from the hydropower plants statistics by the Swiss Federal Office of Energy (SFOE).

$$\frac{PTurbine[MW]}{QTurbine\left[\frac{m^3}{sec}\right] * 3600\left[\frac{sec}{h}\right]} = ConversionFactor\left[\frac{MW}{\frac{m^3}{h}}\right]$$

With this factor the kinetic energy that is available for power production can be calculated. The tunnels have another purpose besides the conversion of water flow kinetic energy. They can also work the other way around and use kinetic energy to pump water in the opposite direction. For the tunnel to pump water, certain conditions have to be fulfilled. First of all, a pump has to be connected to the tunnel to deliver the kinetic energy that is necessary to reverse the water flow. The second condition is that the inlet of the tunnel has to be connected to a reservoir, to another tunnel inlet or a tunnel outlet with another pump. The kinetic energy that is created by the water flow does not have to be used for power production and can be discarded. The kinetic energy for reverse water flow on the other hand has to be produced by pump.

Generator: The generator uses kinetic energy with efficiency losses to produce electric energy.

Pump: The pump uses electric energy with efficiency losses to produce kinetic energy.

River power plant: A river power plant produces electricity directly from the water flow. The interim step with kinetic energy is skipped to reduce the number of variables in the optimization problem. The river power plant has therefore a combination of tunnel and generator equations. But the calculation of the conversion factor is the same method that is used for the tunnels.

Water outflow: The water outflow catches all the water that is leaving the mapped hydro network. This water cannot be used in the hydro network anymore.

The map below shows all hydro elements used in the optimization model for Switzerland and the basins calculated by the HBV model (Figure 19).

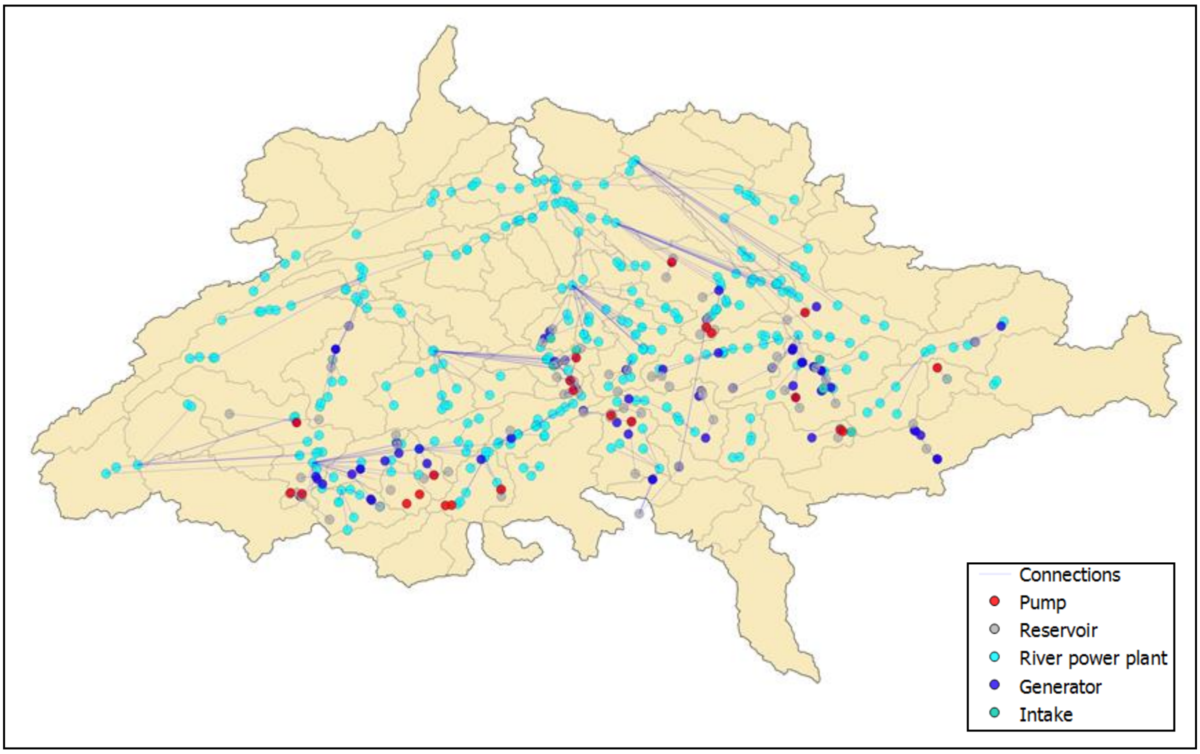


Figure 19: Included power plants in Switzerland with the water connection and the basins

ENTIGRIS: data research

To create the hydro network shown in Figure 19, extensive research and data collection was necessary. The river power plant could be mostly connected by using a calculated streamflow map of the Swiss Alps and then corrected by comparison to maps of the power plants and rivers. The mapping of the reservoirs, tunnel, pumps and generators had to be done mostly by hand. The hydropower plants statistics by the Swiss Federal Office of Energy (SFOE) are the foundation for the mapping. By using schematic of the different cascade systems the components could be connected. The schematic below shows the mapping of the KWO (Kraftwerke Oberhasli AG) hydropower plants (Figure 20).

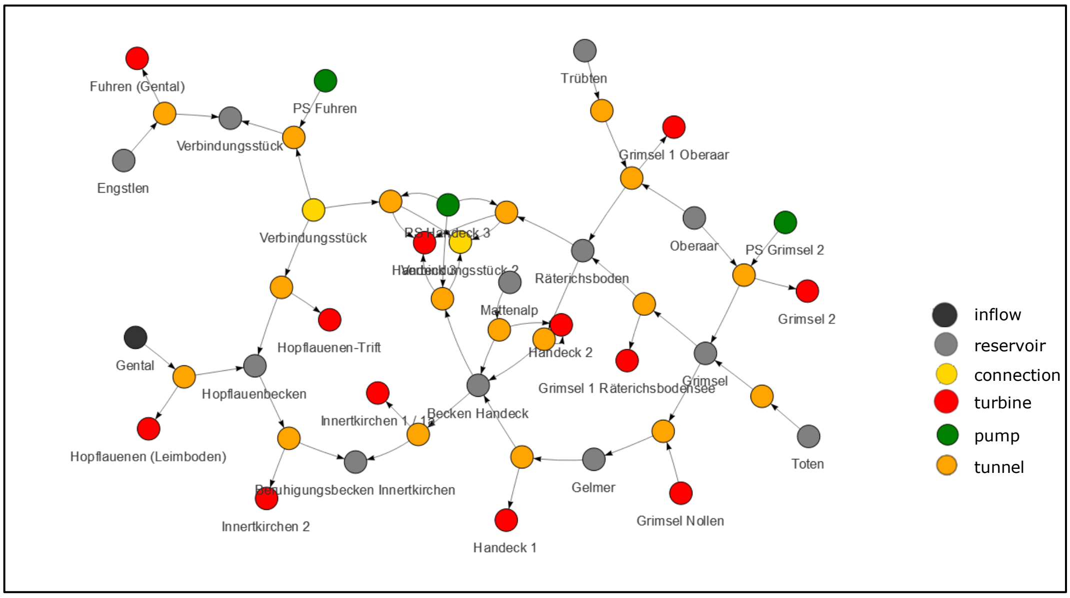


Figure 20: Schematics of the mapping for the KWO hydropower plants

Table 12 : Comparison between the installed capacity and the number of power plants in the hydropower plant statistics and in the ENTIGRIS model

	WASTA	Model	%
Run over River			
Capacity [MW]	4749	4153	87.5%
Number	576	313	54.3%
Turbines			
Capacity [MW]	11437	12190	106%
Number	115	85	73.9%
Pumps			
Capacity [MW]	3,926	3790	96.5%
Number	28	23	82.1%

Table 13 : Comparison between the split of energy production of 2015 and the ENTIGRIS model

Power plant type	Model	Real
Run-of-river	21.62%	25.2%
Reservoir hydro power	39.39%	34.7%
Renewables	2.73%	2.6%
Nuclear	36.12%	33.5%
Gas	0%	2.3%

The schematic shows the connections between the different components (inflow, reservoir, turbine, pump and tunnel) of such a cascade system. There are 30 cascade systems as the one shown above included in the model. The sizes are ranging from a single-digit number of components to a number of components shown above. These cascade systems are connected to the river power plants. Since the study focuses mainly on the future system, new hydro power plants that are in planning or already under construction are included in the mapping as well. Due to this, the turbine capacity in the model is higher than the capacity in the hydropower plants statistics (WASTA) by the Swiss Federal Office of Energy (SFOE). The numbers on the right show the percentage of the produced energy for the 2015 model run and the real values. Due to the higher capacities of reservoir hydro power plants and the perfect foresight of the optimization model there are some differences between the model and the real numbers (Table 13).

Interaction ENTIGRIS and HBV model

Streamflow projections are produced at a power plant scale for 83 hydropower plants. The hydrological basin has been used to process hydroclimatic variables and compute the daily streamflow projection. In addition to that, 125 hydrological basins were proposed as relevant for the analysis of the Alpine water-energy system. These have been used to process hydroclimatic variables and to compute the daily streamflow projection, representative of the water availability in that specific basin.

As in the PRIMES-IEM model, the streamflow has been used to constrain energy production from hydropower plants.

Indeed, water temperature was not needed as we assumed a low impact on thermonuclear cooling efficiency due to temperature increase in the region at 2040.

3.5 TOPKAPI-ETH

For the high spatiotemporal resolution experiment, we adopted the hydrological model Topkapi-ETH (TE). TE is a physically-based, fully-distributed model, originally developed by Ciarapica and Todini (2002) [39] and later improved by the Federal Institute of Technology in Zurich [15][16][40][41]. TE uses a regular grid to represent the topography and a D4 routing method to simulate flow accumulation. The grid cells, which represent the smallest computational elements, are connected using a topographic gradient and the vertical fluxes within each cell are governed by infiltration processes described by empirical formulas. TE explicitly models water infrastructures such as hydropower reservoirs, river diversions, and water abstractions. In each cell, the most relevant hydrological processes are taken into account (Figure 21).

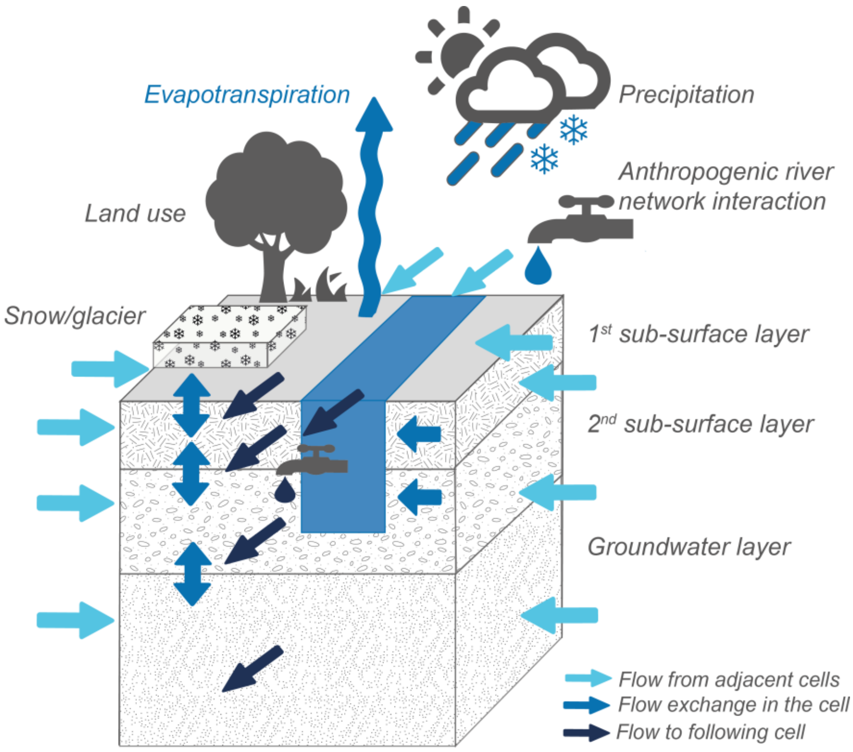


Figure 21: Hydrological processes modelled in TOPKAPI-ETH

Interaction ENTIGRIS and TOPKAPI-ETH model: Soft model integration methodology

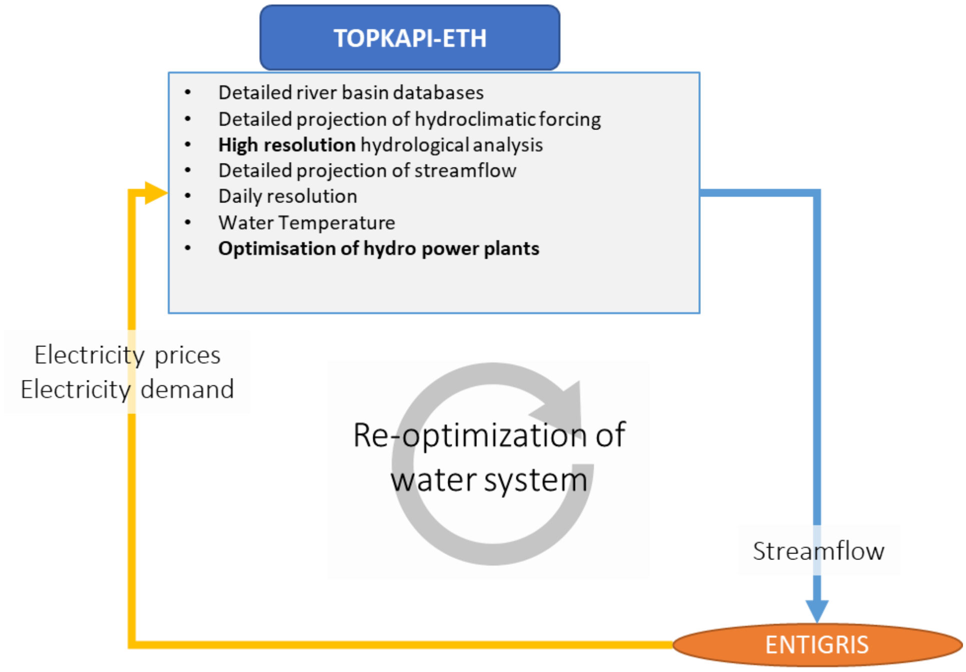


Figure 22. Soft-integration scheme designed for the integration of ENTIGRIS and TOPKAPI-ETH.

We designed the soft integration of the water and energy models as outlined in Figure 22. The soft model integration consists in optimizing jointly the water and energy systems by an iterative loop. First, the water system model (i.e., TOPKAPI-ETH) optimizes the hydropower reservoir operations producing streamflow trajectories as output. These are used as input to the energy system model (i.e., ENTIGRIS) as water availability constraint. ENTIGRIS optimizes the energy system producing electricity prices and demand trajectories and passes this information to TOPKAPI-ETH, which again optimizes the hydropower reservoir management. A new trajectory of streamflow is computed and feeds the energy system model for a new round of optimization of the energy system. The process is repeated iteratively until convergence is reached among streamflow, electricity price, and demand trajectories. This methodology allows an information exchange between the two systems models in order to find a solution optimized with respect to both water and energy systems.

4 Scenario construction and description

4.1 Hydrological modelling chain

In the analysis, three different approaches have been explored to study the water-energy nexus (Figure 10). The first aims at providing streamflow and air temperature for constraining hydropower and thermoelectric production in the electricity model PRIMES-IEM. The scheme is reported in Figure 23.

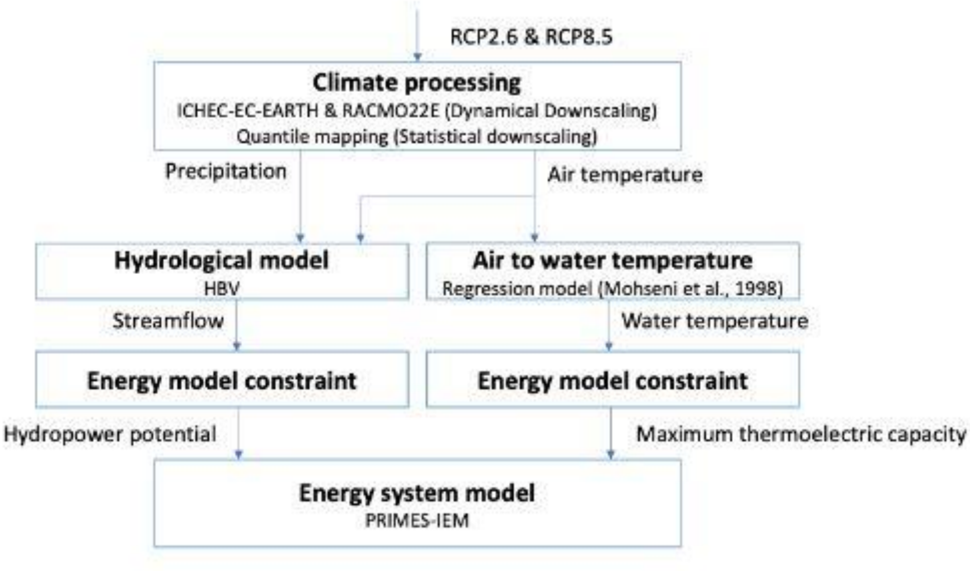


Figure 23: Modelling chain for the interaction HBV – PRIMES.

As stated before, only the streamflow was provided to constrain hydropower production in the ENTIGRIS model. The scheme used to achieve this objective is shown in Figure 24.

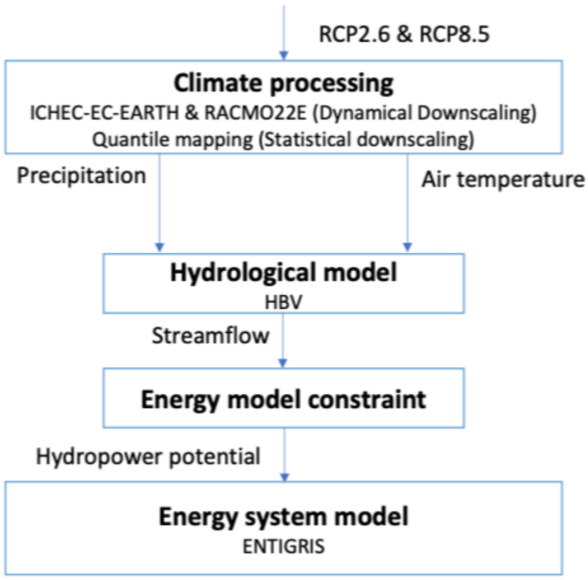


Figure 24: Modelling chain for the interaction HBV – ENTIGRIS.

Finally, for the Adda river basin high resolution case study, a soft integration approach has been implemented. The model TOPKAPI-ETH has been used to provide streamflow and compute generation of the hydropower plants included in the basin. These values were used in a feedback loop with the model ENTIGRIS until convergence on the same solutions. The methodology is summarized in Figure 25.

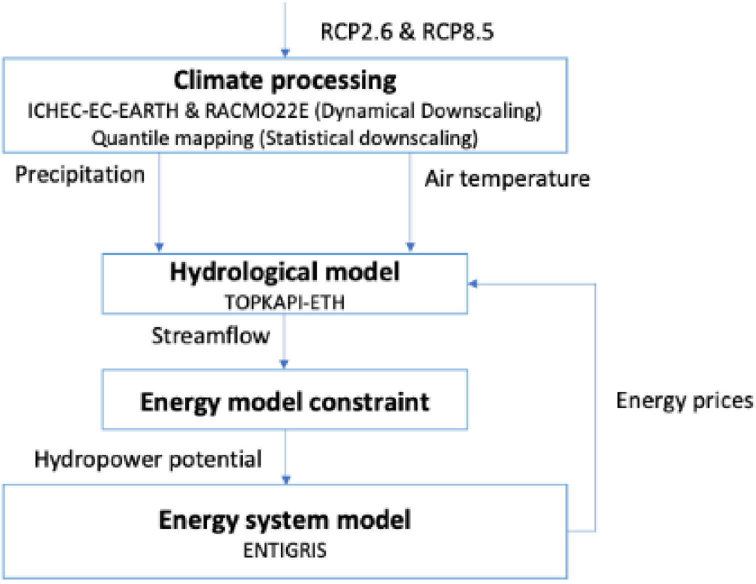


Figure 25: Modelling chain for the interaction TOPKAPI-ETH – ENTIGRIS.

The meteorological data required to calibrate the hydrological models have been pre-processed. These data include climatic variables, i.e., precipitation and temperature, and streamflow data for calibration. In particular, for the Danube region, Iberian Peninsula and part of Alpine region analysis we adopted a power plant scale, i.e. the hydrological model output is set at the closest possible inlet of the power plant (for a detailed description see Supplementary Material Watershed delineation). Conversely, for some Alpine basins the basin area was already provided.

Therefore, for each power plant (57 in the Danube region and 110 in the Iberian Peninsula, 95 in the Alpine region), we delineated the corresponding catchment basin, i.e., the area of land where precipitation collects and drains off into the selected point or outlet. Starting from the DEM provided by the European Environmental Agency[9] and by using the software ArcGIS, we followed the procedure required to delineate a watershed (through a group of functions included in the ArcGIS Spatial Analyst tool) given the geographical coordinates of a specific point, which in our case represented a power plant (hydropower, nuclear, or thermal). For a detailed description of the procedure, see Supplementary Materials, S.1. Watershed delineation.

As an example, Figure 26 and Figure 27 illustrate the results of the power-plant basin delineation for the Danube region and the Iberian Peninsula, respectively. Black dots are the considered power plants, while the associated catchment areas are marked through the grey lines and filled with different colors.

[9] https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-eu-dem

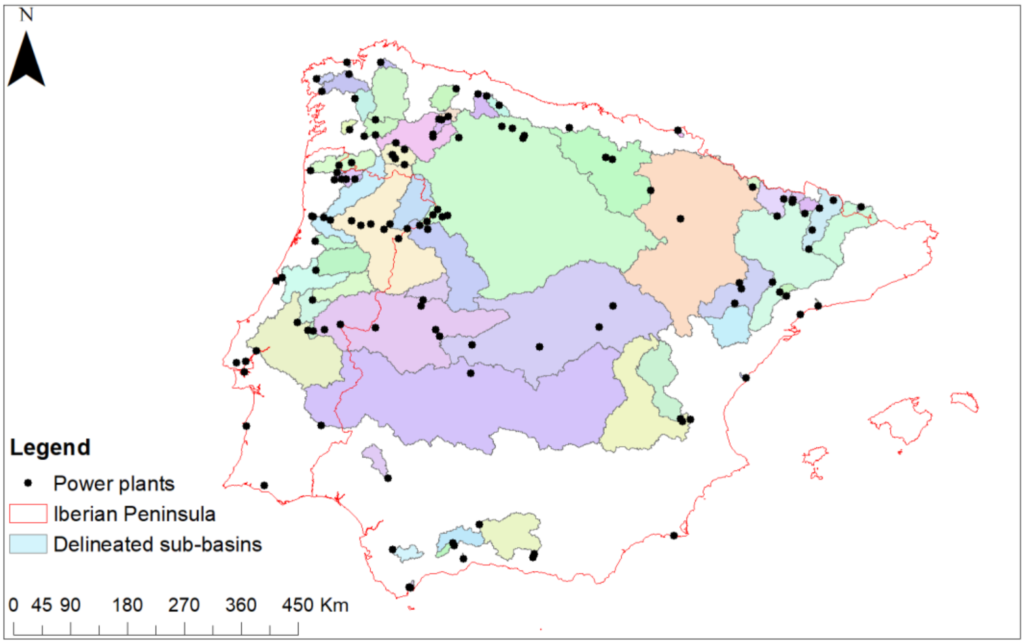


Figure 26: Delineated basins at the power-plant scale for the Iberian Peninsula.

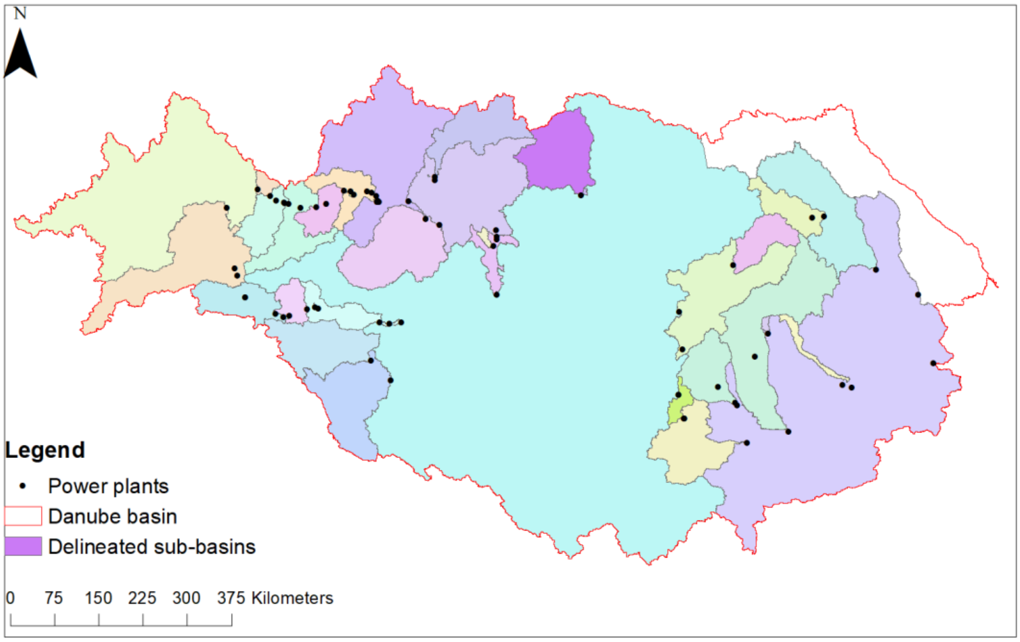


Figure 27: Delineated basins at the power-plant scale for the Danube region.

Processing of hydroclimatic variables

The whole analysis stems from the choice of two RCPs provided by the IPCC. These two are RCP2.6 and RCP8.5 from the IPCC Fifth Assessment Report [18]. RCP2.6 represents an optimistic scenario, where emissions peak and decline early in this century leading to very low climate change, while RCP8.5 represents a high-emission and no climate policies scenario leading to catastrophic climate change. Therefore, these two scenarios can be considered as giving a lower and upper bound with respect to the climate change effects that are expected to happen in the next decades.

In Figure 28 the whole climate projections processing chain is reported. Simulations of ICHEC-EC-EARTH (General Circulation Model) were dynamically downscaled using RACMO22E (Regional Climate Model). These data were available thanks to the CORDEX project. As mentioned in 0 local observations were used to remove potential RCM biases via quantile mapping, thus generating more accurate local estimate of the hydroclimatic variables of interest, i.e. precipitation and air temperature. This combination of dynamical and statistical downscaling is usually referred to as combined downscaling in the scientific literature [21].

The procedure described above was followed in order to produce the input variables needed for all the hydrological models, both HBV and TOPKAPI-ETH. The observational datasets used for the statistical downscaling are reported in Table 14, the projections are reported in Table 15.

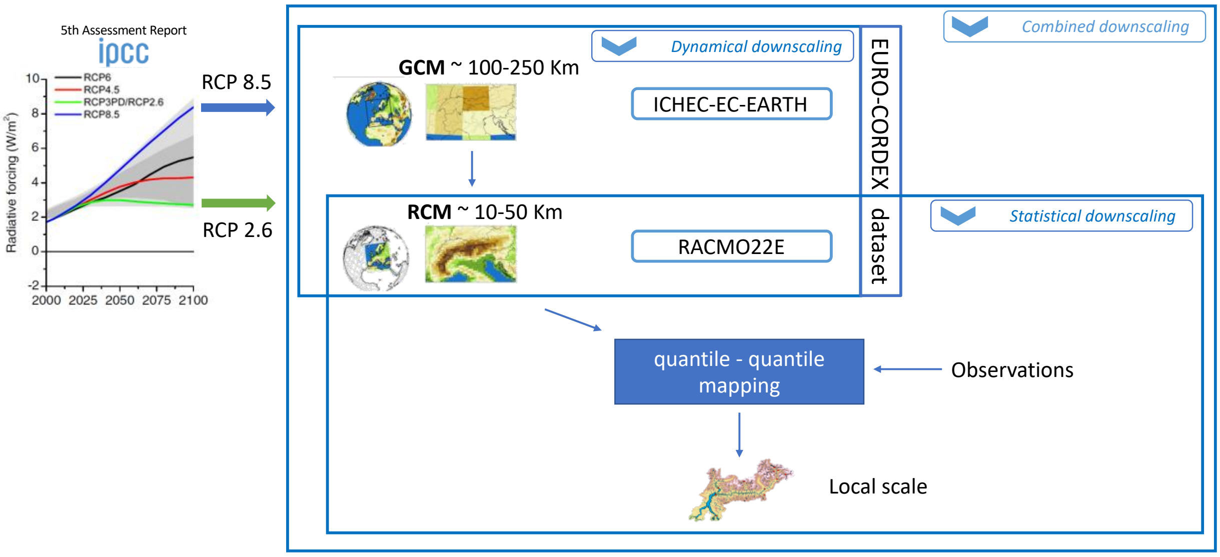


Figure 28: Climate projections processing chain.

	Institution	Area	Format	Spatial resolution	Temporal resolution	Period
Precipitation	Federal Office of Meteorology and Climatology MeteoSwiss, Dataset EURO4M-APGD	European Alps	Gridded dataset	5 km	daily	1971-2008
	Royal Netherlands Meteorological Institute (KNMI), Dataset E-OBS	Europe, North Africa and the Middle East	Gridded dataset	25 km	daily	1950-2017
Temperature	Royal Netherlands Meteorological Institute (KNMI), Dataset E-OBS	Europe, North Africa and the Middle East	Gridded dataset	25 km	daily	1950-2017

Table 14: Observational datasets used in the statistical downscaling.

	Institution	Area	Format	Spatial resolution	Temporal resolution	Period
Precipitation	EURO-Cordex Dataset	Europe	Gridded dataset	12,5 km	daily	1950-2006 2006-2100
Temperature	EURO-Cordex Dataset	Europe	Gridded dataset	12,5 km	daily	1950-2006 2006-2100

Table 15: Hydroclimatic variables projections datasets used in the analysis.

HBV calibration and validation results

The HBV model has been used extensively in the analysis. On the whole, 375 HBV models were calibrated and validated. Such a large scale analysis would have required observed flow at 375 different geographical points. Given the lack of these data, all these models were calibrated and validated using data coming from LISFLOOD simulations over the period 1990-2016 as observed data. LISFLOOD is a distributed hydrological model covering the whole Europe with a resolution of 25 square kilometers. These data were provided by JRC, which is the developer of the model[42][43]. The data used are described in Table 16.

	Institution	Area	Format	Spatial resolution	Temporal resolution	Period
Discharge	JRC LISFLOOD model	Europe	Gridded dataset	5 km	daily	1990-2016

Table 16: Discharge data (LISFLOOD model output) used for calibration and validation of HBV models.

For each point where streamflow projection was needed, the corresponding cell of the LISFLOOD model was identified. LISFLOOD streamflow values were split into a calibration (1990-2005) and validation (2006-2016) sets used to tune the parameters of the HBV models.

The main limitations of this approach are two:

- Given that LISFLOOD itself is a model, the quality of the HBV models can be evaluated with respect to the one of LISFLOOD. The LISFLOOD model was developed for flood control and therefore it is expected to be reliable in streamflow prediction. At the same time, LISFLOOD needs to cover a very large area and it does not necessarily prove to be accurate over all the European domain.

- The size of the cell in LISFLOOD constrained the quality of the HBV models developed, especially where the corresponding basin was smaller than 25 km^2. Factors based on the ratio between basin area and LISFLOOD cell area were applied to bias correct the streamflow calibration values in order to improve the quality of the model.

As an example, some results for the hydropower plant Belesar in northern Spain are reported. Figure 29 shows the map of the basin and the main river network, Figure 30 shows the trajectory of observed and simulated data for calibration and validation. The model performs quite well in term of Nash-Sutcliffe Efficiency[10], reported in Table 17.

Table 17: Calibration and validation statistics for the Belesar HBV model.

	Calibration	Validation
NSE	0.9539	0.9119

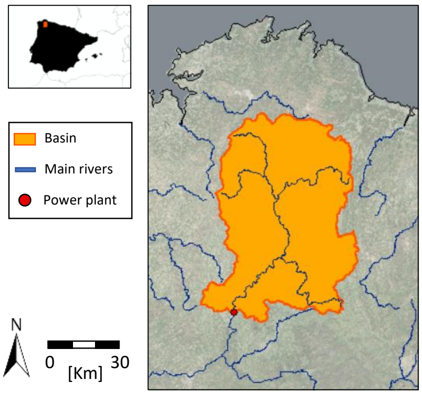


Figure 29: Belesar hydropower plant: map and hydrologic basin. Basin area is 4274 km^2.

[10] Nash-Sutcliffe efficiency is an index showing how well the model can explain the observed data, its ideal value being equal to one.

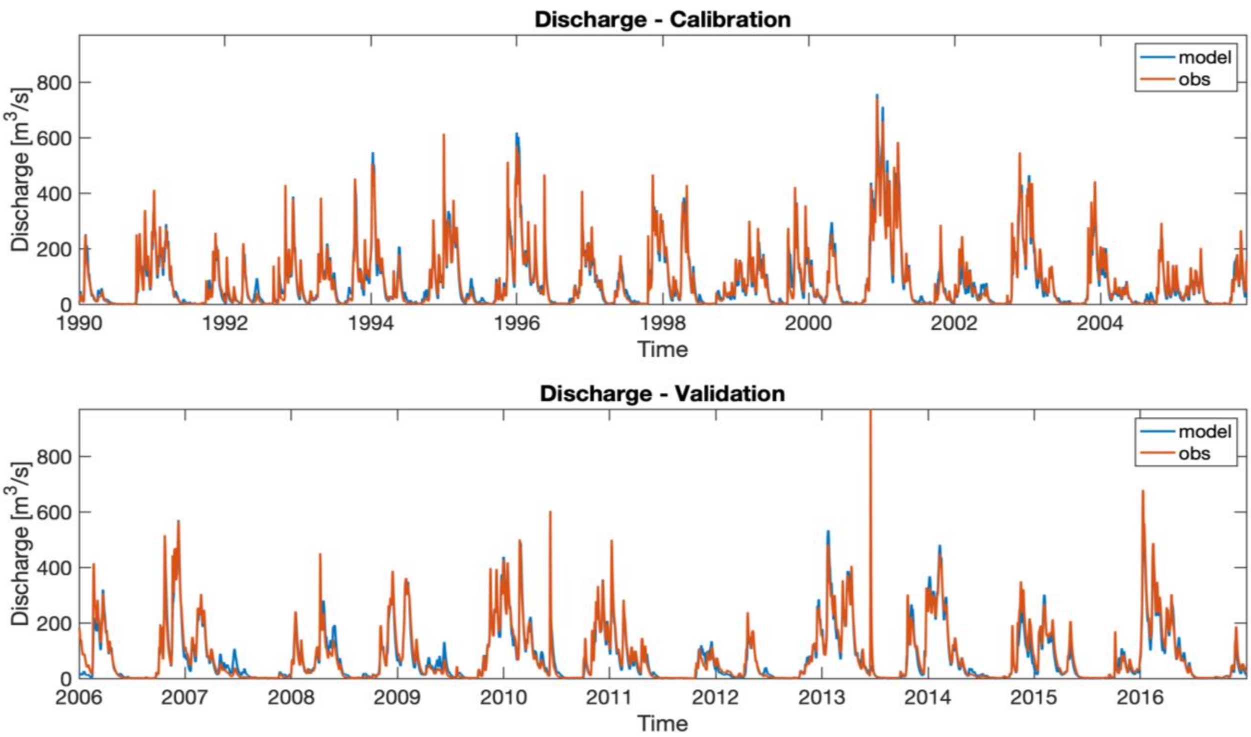


Figure 30: Calibration and validation trajectories of streamflow for Belesar hydropower plant, Spain.

Statistics for the whole regions are reported in Figure 31 and Figure 32.

Results are good across the regions analyzed. However, it is easy to see that HBV models provide better results for the Iberian Peninsula, where usually the basins where larger and located downstream along river basins. Results are worse in regions where difficulties were encountered due to the small size of the basin. Indeed, that created some problems in the Swiss and Italian alpine region and in the upper Danube river basin. As mentioned before, a model output is used as observational data in the calibration process. In fact, streamflow data from LISFLOOD were corrected to remove diversions and effects due to reservoirs in order to have the natural streamflow. Anyway, in some regions, streamflow still showed a recognizable pattern. Therefore, calibrating the model against controlled data did not produce good results.

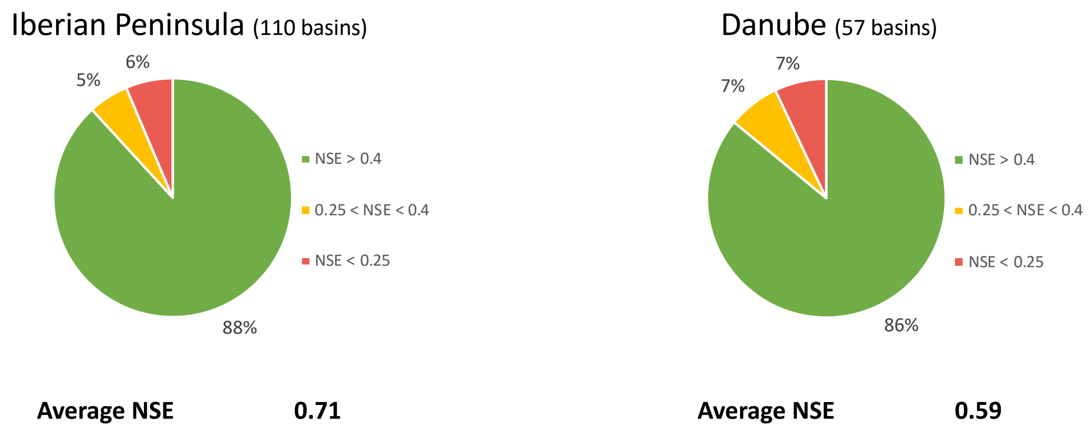


Figure 31: Validation results for Iberian Peninsula (left panel) and Danube region (right panel).

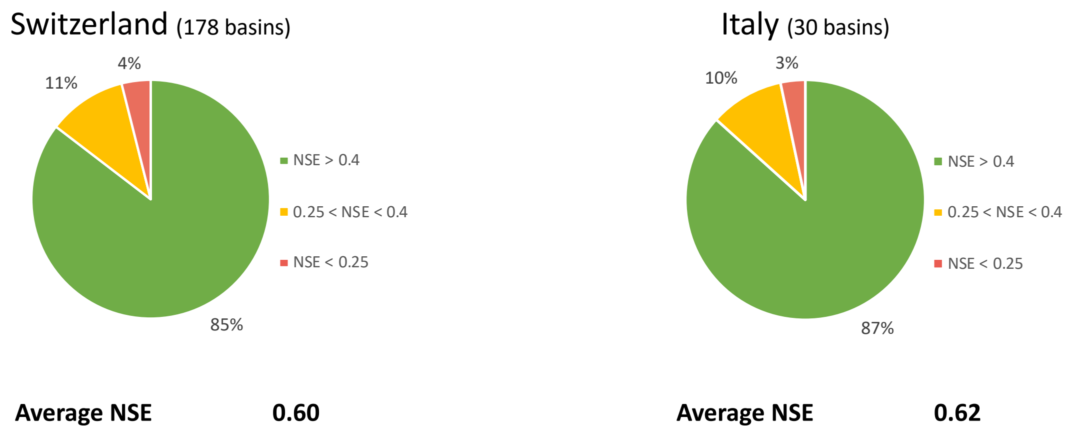


Figure 32: Validation results for Alpine region: Switzerland (left panel) and Italy (right panel).

TOPKAPI-ETH calibration and validation results

A TOPKAPI-ETH model of the Adda River basin has been calibrated using hydroclimatic data over the period 2011-2013, as explained in section 3.5. Table 18 shows the model performance using the Nash-Sutcliffe Efficiency (NSE) and additionally showing root mean square error (RMSE), and Kling-Gupta efficiency (KGE) computed over the validation period 2008-2010. In this case, carefully assessing the quality of the model is fundamental. Indeed, feedbacks between hydropower production and energy system prices are better observable with a high spatial and time resolution, only if the model can guarantee a high accuracy. Figure 33 shows the comparison between the observed (black line) and the simulated (blue line) inflow for the validation year 2010, as an example. Considering the spatial (250 m^2) and the temporal (daily) resolution adopted, both the metrics and the reservoir inflow trajectories show that the model is able to reproduce with high level of accuracy the historical inflow.

Table 18: Performance of the Topkapi-ETH model over the validation period for the two main hydropower reservoirs (HP1 and HP2 in Figure 33). HP1 is Cancano reservoir, who is further analyzed in the soft integration methodology.

Performance metrics	HP1	HP2
NSE [-]	.90	.88
RMSE [m3/s]	4.25	1.92
KGE [-]	0.94	0.86

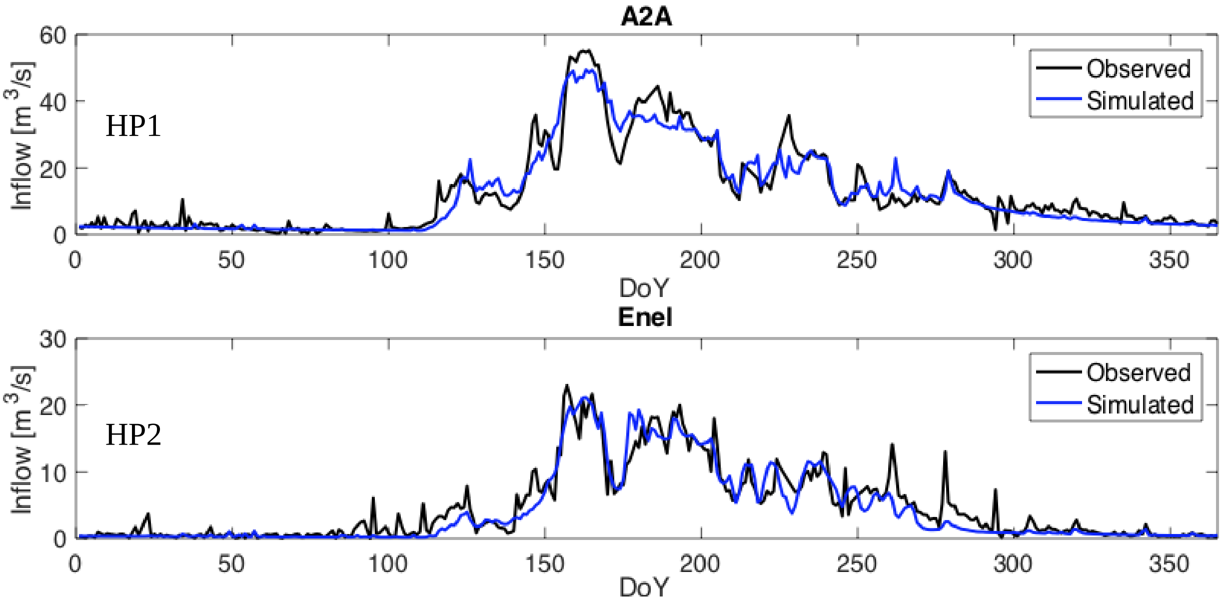


Figure 33: Observed versus simulated inflow data over the validation period 2008-2010.

4.2 Scenarios for the power models

Scenarios for the PRIMES-IEM power model

A wide range of scenarios was selected, in order to examine the interdependency of water and energy. At first, a current water availability and climate conditions scenario has been examined, serving as a reference case. The distinction among the rest of the scenarios is based on climate conditions (RCP8.5 or RCP2.6) and the precipitation levels (average, dry, extreme dry).

The energy system simulation is based on the EUCO scenarios, which were part of the impact assessment of the proposals included in the "Clean Energy for all Europeans

Package". The EUCO policy scenarios were built on the EU Reference Scenario 2016 [10] and aimed at achieving the 2030 targets (decided by the European Council). The scenarios involve GHG emissions reduction of 40% in 2030 (compared to 1990), 27% RES in total gross demand for energy and 30% lower total primary energy by 2030 relative to a projection performed using PRIMES back in 2007[11]. The EU scenario is a scenario which aims at reducing energy system emissions in 2050 by at least 80%. The solution of the capacity expansion problem under these conditions was taken for granted in the simulations performed with the PRIMES-IEM unit commitment simulator.

In the context of this study different scenarios for the 2040 electricity system were simulated for both the Iberian Peninsula and the Danube River Basin region. The ***2040 reference scenario*** (REF2040) simulates the future electricity system with no water constraints enabled, as if water availability was the same as the historical average. Based on the REF2040, 6 scenarios were quantified taking into account the constrained water availability for power generation and were named after the climate condition (RCP2.6 or RCP8.5) and the level of precipitation (Average, Dry, Extreme-dry) assumed: ***RCP2.6Average***, ***RCP2.6Dry***, ***RCP2.6Extremedry***, ***RCP8.5Average***, ***RCP8.5Dry,*** and ***RCP8.5Extremedry*** (Table 19). The scenarios are based on a statistical analysis of the annual precipitation over the whole region of interest (Iberian Peninsula and Danube region) for both RCPs scenarios over the 20-year period 2040-2060. The average scenario is simulated considering the water availability from the year when the median annual precipitation is observed. The extreme dry scenario uses the water availability from the driest year. Dry scenario relies on water availability from the year characterized by an annual precipitation that is closest to the 25th percentile over the historical period (1984-2004).

Table 19: Scenarios Description

Scenario Name	Climate Conditions			Precipitation Level		
	Reference	RCP2.6	RCP8.5	Average	Dry	Extreme Dry
REF2040	✓					
RCP2.6Average		✓		✓		
RCP2.6Dry		✓			✓	
RCP2.6ExtremeDry		✓				✓
RCP8.5Average			✓	✓		
RCP8.5Dry			✓		✓	
RCP8.5ExtremeDry			✓			✓

11 Although during the summer of 2018 the renewable targets have been updated, this study remains nonetheless valid as it provides an indication of why and in what order of magnitude flexibility and storage are needed to the horizon of 2030.

Scenarios for the ENTIGRIS power model

Six scenarios are evaluated for the alpine region in this study. The key differences between the scenarios are set by the assumptions for flexibility, climate developments and demand (see Table 20 below).

Table 20 : Scenario assumptions for the alp region

Scenario	Year	Flexibility	Climate	Demand
Scenario Today	2015	Today	RCP2.6	Today
Scenario Standard	2040	Normal	RCP2.6	Increase
Scenario HighFlex	2040	High	RCP2.6	Increase
Scenario Standard 8.5	2040	Normal	RCP8.5	Increase
Scenario HighDemand	2040	High	RCP2.6	High Increase
Scenario HighRES-Flex	2040	High	RCP2.6	High Increase

The first scenario is the today scenario, which serves as a reference for the other scenarios, to compare and determine the differences between the current energy water system and the ones in the future. Therefore, the flexibility, the climate and the demand represent the year 2015. Figure 34 shows the installed capacity for all 5 countries in year 2015.

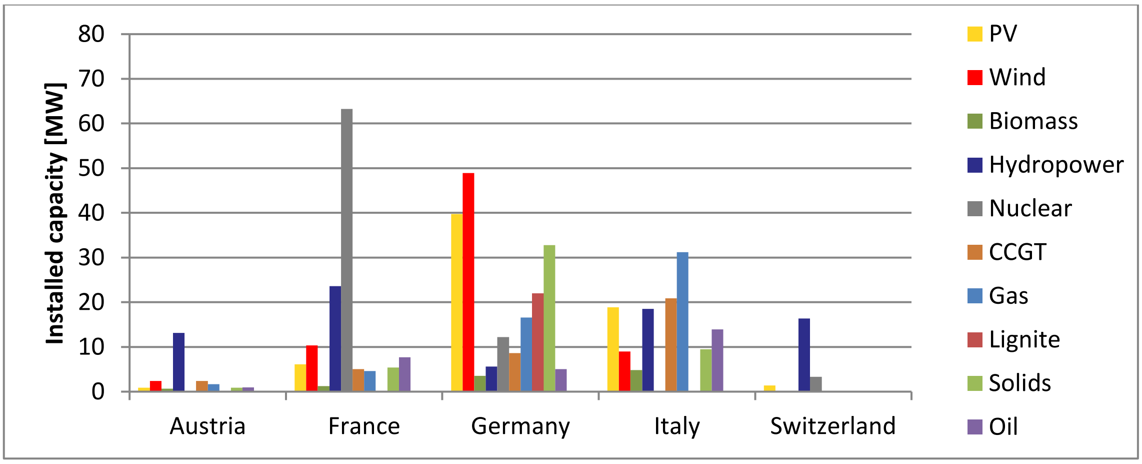


Figure 34: Installed capacity for the reference scenario (2015)

The Standard scenario represents the year 2040 with a moderate development. The flexibility stays the same as today and the climate scenario is moderate with the RCP2.6 scenario. The demand increases due to a moderate sector coupling which increases the electricity demand. The electricity demand is increased between 17-33 % compared to the reference (today) scenario.

The scenario HighFlex is similar to the Standard scenario with the exception of the flexibility. The high flexibility means that it is assumed that the installed turbine capacity of all reservoir power plants in Switzerland is doubled by 2040 compared to the 2015 capacity. The pumping capacity is tripled compared to the 2015 capacity. The available amount of water is the same as in the standard scenario, but due to the higher capacity the system is more flexible.

The Standard 8.5 scenario is similar to the Standard scenario except for the climate projections that are used. The standard 8.5 scenario uses the RCP8.5 climate projections which have radiative forcing of 8.5 W/m². The other scenarios are calculated with the RCP2.6 scenario which has a radiative forcing of 2.6 W/m².

The HighDemand scenario consists of an even higher demand increase than the scenarios before and high flexibility.

The HighRES-Flex scenario is similar to the HighDemand scenario with the exception of increased wind and solar capacities. The capacities of the HighRES-Flex scenario can be seen in Figure 35 below, including the higher hydro capacity in Switzerland and the higher RE capacities in all countries. Furthermore, the capacities for conventional power plants are smaller in all countries compared to 2015. There are no more lignite and nuclear power plants in Germany and the capacity of solid power plants is smaller as well. Switzerland and Italy have phased out nuclear and solid power plants respectively as well.

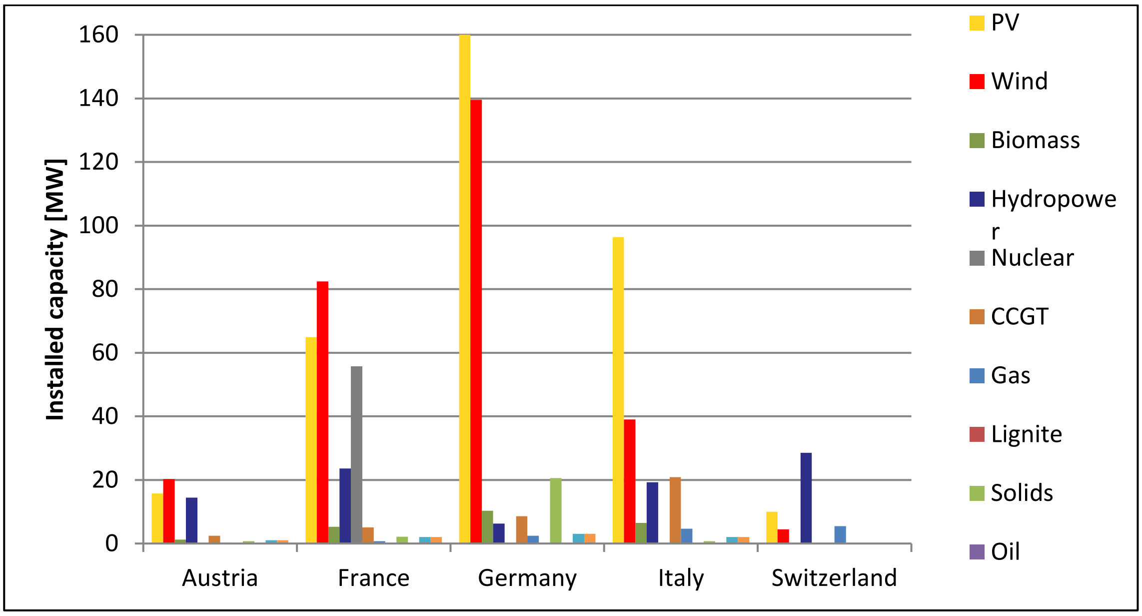


Figure 35: Installed capacity for the HighRES-Flex scenario (2040)

5 Results

5.1 *Iberian Peninsula*

Hydroclimatic analysis

As for the hydroclimatic variables projections illustrated in Figure 36, it is easy to notice the difference between the two RCP scenarios. Indeed, the RCP8.5 implies large changes while the RCP2.6 does not depart much from the historical conditions, which are computed over the timespan 1984-2004. Precipitation and temperature over the Iberian Peninsula under RCP2.6 are not fundamentally changed at the end of the century (yellow line) with respect to historical conditions (red line): temperature increases of a few degrees and precipitation is a bit heavier in the first months of the year while it's lower at the end. On the other hand, under the RCP8.5 scenario at the end of the century temperature increase substantially (almost +4°C) during all months and precipitation is largely reduced throughout the year, especially during spring and autumn.

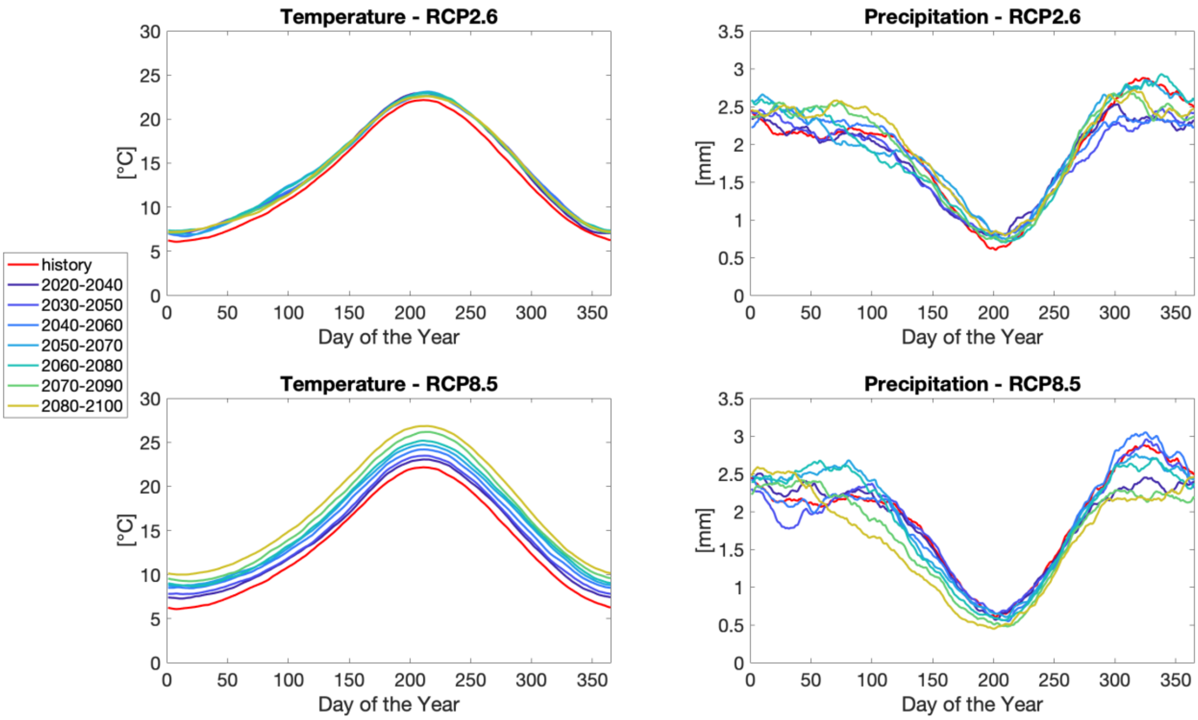


Figure 36: Iberian Peninsula average temperature and precipitation projections for the next decades under RCP2.6 (top panels) and RCP8.5 (bottom panels) scenarios. The color of the lines shows the time period considered in order to describe the evolution in time of these variables. The lines reported are the cyclostationary average over the time period considered.

In Table 21 average annual precipitation and temperature for the whole Iberian Peninsula are reported for historical conditions 1984-2004 and at 2040-2060 under RCP2.6 and RCP8.5 scenarios.

Table 21: Average annual temperature and precipitation for Iberian Peninsula: historical conditions (1984-2004), RCP 2.6 (2040-2060) and RCP 8.5 (2040-2060).

	1984 - 2004	RCP2.6 (2040-2060)	RCP8.5 (2040-2060)
Temperature [°C]	13.3	14.2	15.4
Precipitation [mm/y]	690	690	684

Considering the twenty-year period used throughout the analysis, it is possible to extract relevant statistical information about precipitation over the whole Iberian Peninsula and changes in probability of occurrence of dry years. In Figure 37 the cumulative distribution of annual precipitation is reported. Under the RCP2.6 scenario precipitation is usually lower than historical one, especially in median and 25th percentile but the maximum is the highest among all the distributions. Under RCP 8.5 the median is not much different from the historical one, but the maximum value is much larger and percentiles are lower between 0.2 and 0.5 cumulative probability values (i.e. more probability of lower annual precipitation values).

Considering the 25th percentile over the control period as an average dry year, we can also conclude that the probability of such events is going to increase of 11% and 6% under RCP 2.6 and RCP 8.5 respectively.

The variability increase in the distribution of annual precipitation is shown in the histograms in Figure 38. Both RCP 2.6 and RCP 8.5 show more spread distribution and higher frequency of low annual precipitation.

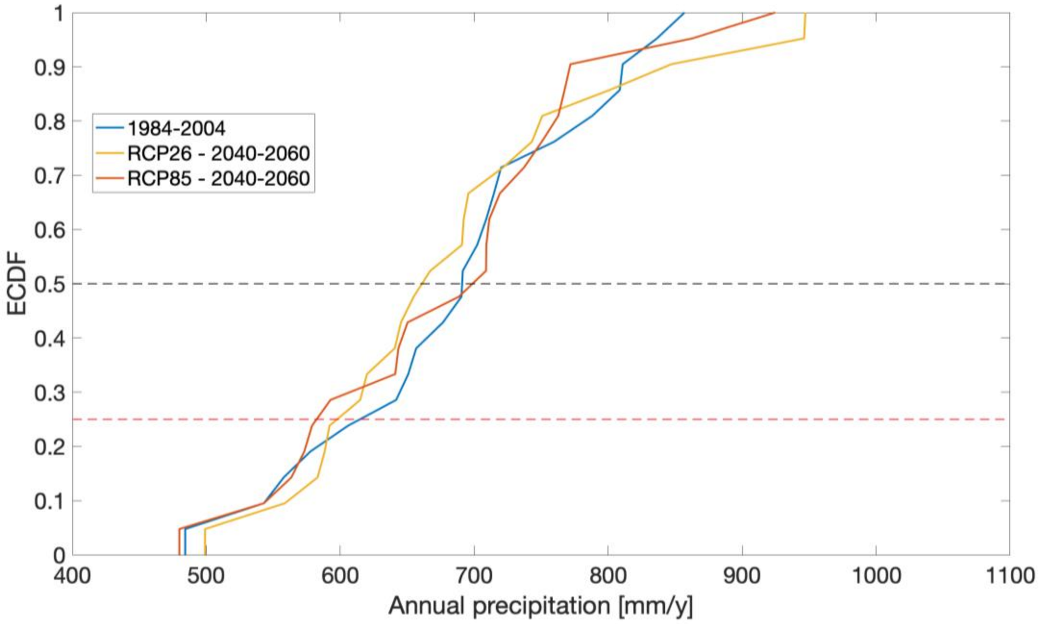


Figure 37: Empirical cumulative distribution of annual precipitation in Iberian Peninsula for control period (blue) , RCP 2.6 (yellow) and RCP 8.5 (red) over the time-span 2040-2060. Black dashed line intersects the median, while the red dashed one intersects the 25th percentile for each scenario considered.

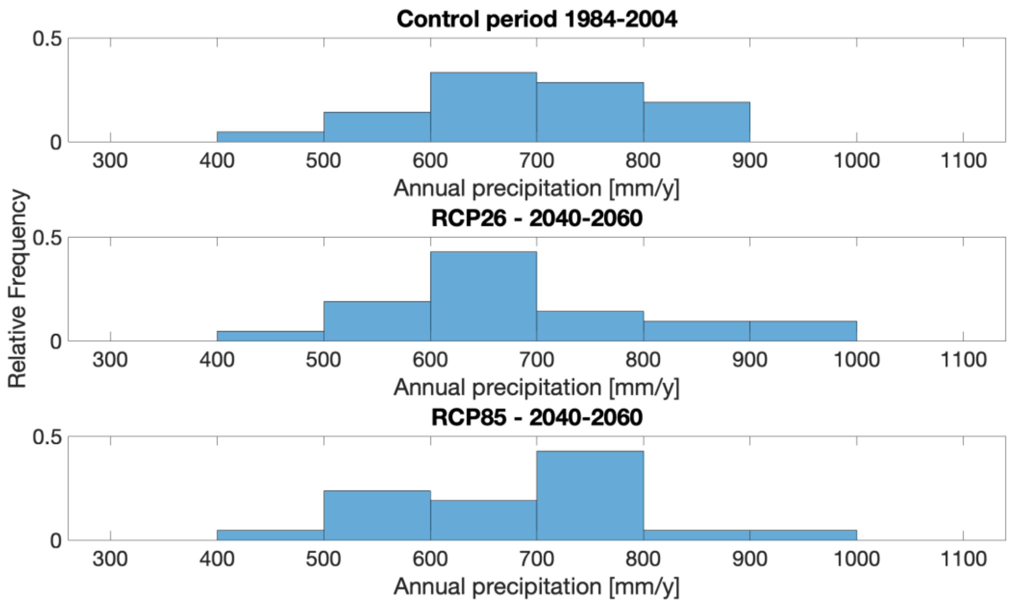


Figure 38: Histogram of annual precipitation over Iberian Peninsula for control period (top), RCP 2.6 (middle), RCP 8.5 (bottom).

To better understand the projected impacts of climate change, we deepened the analysis by looking at the spatial variability of climatic trends focusing on the major river basin illustrated in Figure 39. Disaggregating the information for each single basin, it is easy to notice that temperature increase is consistent in the entire region (Figure 40, top panel). On the other hand, precipitation shows increase or decrease depending on the position of the basin: basins on the west coast are likely to get drier under RCP2.6 but wetter under RCP8.5. The basins in the south and in the east show the opposite trend (Figure 40, bottom panel). This spatial heterogeneity in climate projections is partially transferred to the projected stream flows (Figure 41). Basins in the south and in the east will experience reduced streamflow under RCP2.6 and even more under RCP8.5. Basins in the west will experience drier conditions under RCP2.6, but under RCP8.5 flow will be less affected, and it will increase in particular cases (e.g. Mino Sil basin, Figure 41: Average annual streamflow and its delta with respect to historical conditions for some major river basins in Iberian Peninsula. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow and RCP8.5 2040-2060 in red.Figure 41).

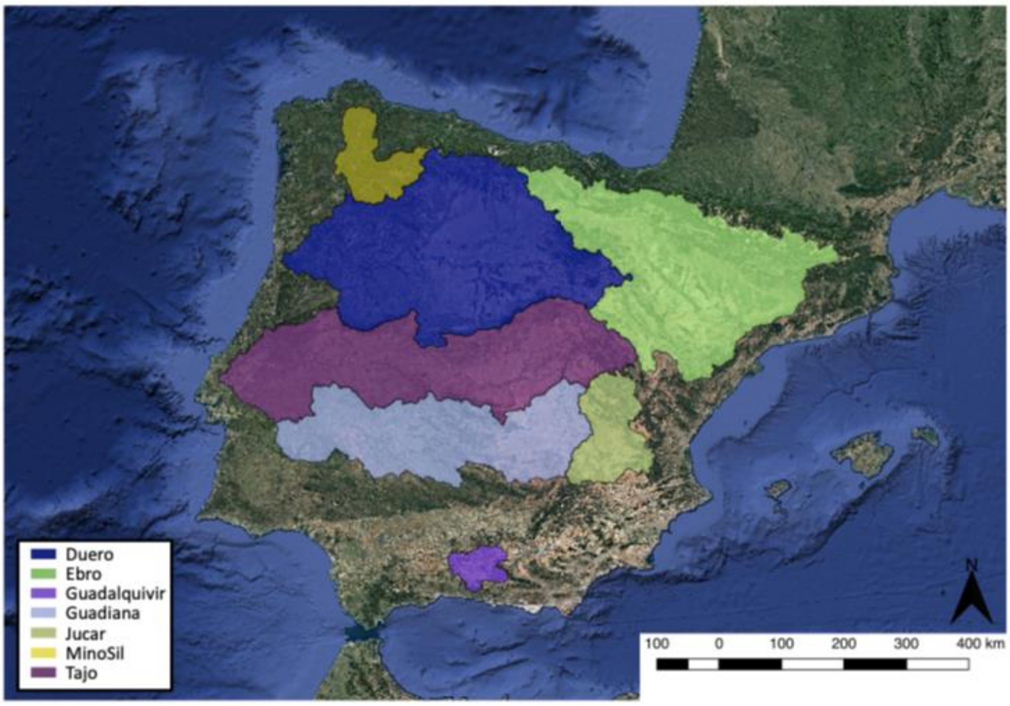


Figure 39: Basins analysed to evaluate the spatial heterogeneous effect of climate change in the Iberian Peninsula. Smaller basins are used as proxy to evaluate the effect on whole basins.

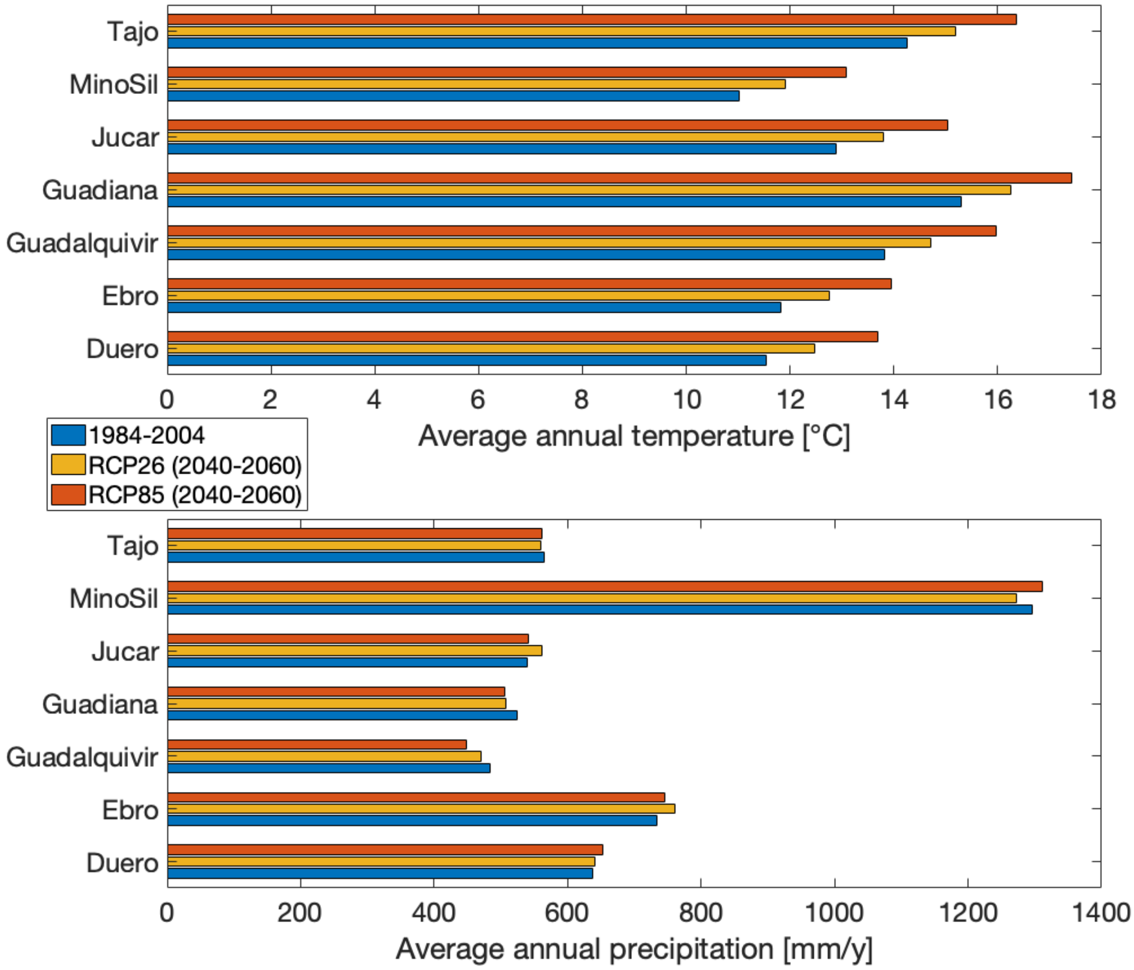


Figure 40: Average annual precipitation and temperature over the main river basins in Iberian Peninsula. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow, RCP8.5 2040-2060 in red.

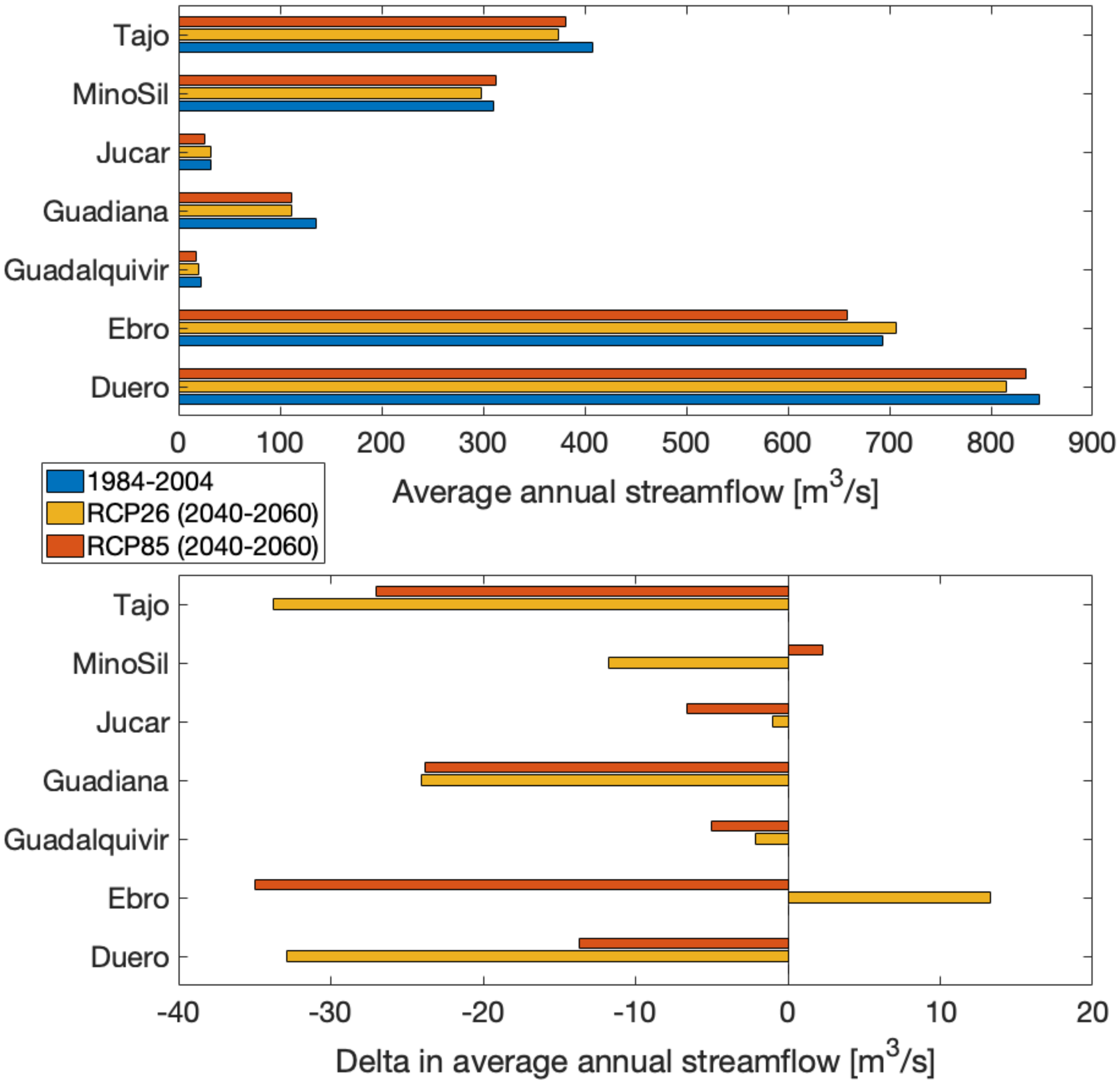


Figure 41: Average annual streamflow and its delta with respect to historical conditions for some major river basins in Iberian Peninsula. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow and RCP8.5 2040-2060 in red.

If the single power plants’ water availability and temperature are considered, large variability can be observed. For example, the projections for the Belesar hydropower plant are reported in Figure 42. Thick lines report the cyclostationary average over 20-year period for historical (1984-2004) and future conditions (2040-2060) for both RCPs analyzed. The thin lines in the background correspond to each single year realization. The effects of the RCP2.6 prove to be mild with respect to the RCP8.5 also in this case. The average streamflow does not change much, and its distribution is similar to the historical one in RCP2.6. On the other hand, under RCP8.5 scenario, the average stream flow decreases and its distribution in time changes too with a peak in winter and a substantial decrease in spring and autumn. Variability of stream flow can be observed measuring the magnitude of the envelope in the background of lines with the same color (i.e. corresponding to the same period-scenario couple). The envelope of the RCP2.6 (yellow) is significantly smaller than the RCP8.5 (red one). Indeed, red trajectories display very large peaks and very low-flow periods over the 20 years.

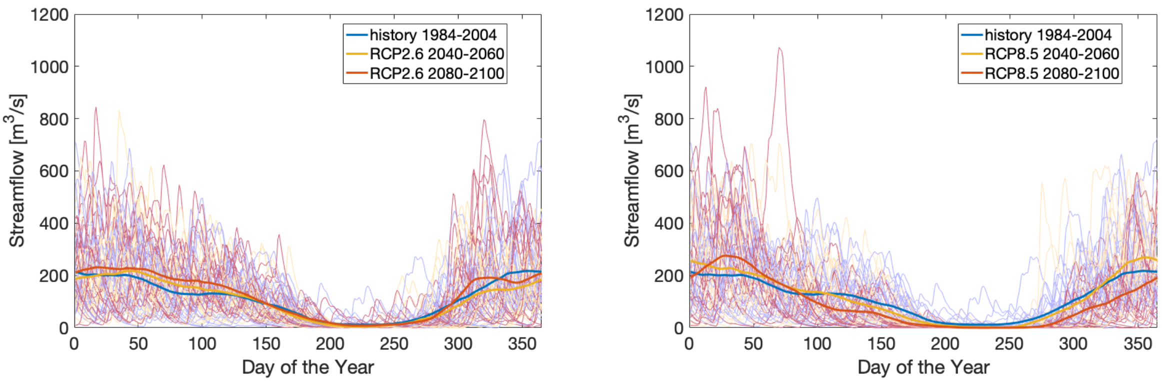


Figure 42: Streamflow projections for Belesar hydropower plant under RCP2.6 (left panel) and RCP8.5 (right panel). The color of the lines refers to different time intervals. The faded thin lines in the background show each single year streamflow trajectory for the period considered while the thicker ones represent the cyclostationary average over the period.

Comparison between 2015 and 2040 power system in a EUCO context

The electricity system of the Iberian Peninsula for 2015 is heavily dependent on thermal and nuclear power generation, while variable renewables (i.e. wind-onshore, wind-offshore, solar, etc.) and hydroelectric power generation cover one third of the total power generation as shown in Figure 43. Moving towards 2040 driven by ETS prices in the decarbonisation context, the generation mix of the Iberian Peninsula decarbonises significantly, with RES (including hydro plants) holding the largest share - over 80% - and nuclear covering 12% of the generation. Fossil fuel generation has decreased drastically due to high ETS prices, as the share of solids and CCGT in power generation drops almost to 1%.[12]

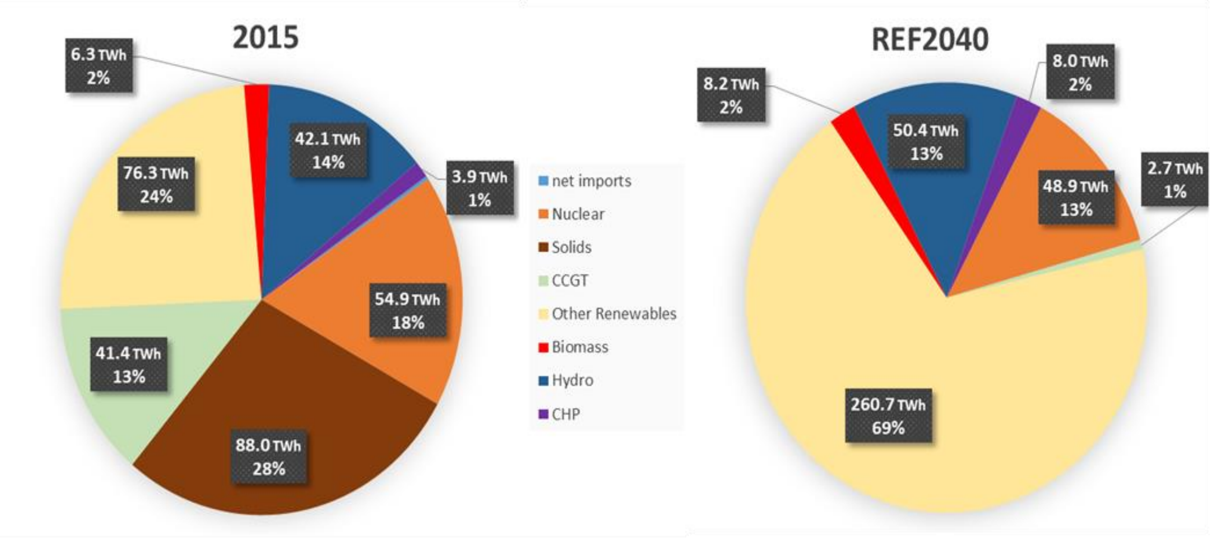


Figure 43: 2015 and 2040 power generation mix of the Iberian Peninsula.

12 The projections for Spain do not include the pledge –announced in November 2018- to work towards 100% renewable energies by 2050

Figure 44 presents the CO_2 emissions and the carbon intensity of the power generation for the Iberian Peninsula for the year 2015 and 2040, where the extent of the emission reduction in the Iberian Peninsula becomes evident. The CO_2 emissions from power generation decrease by 95%, in 2040 with respect to 2015 levels. Carbon intensity of power generation, following a similar trend, reduces by 96%.

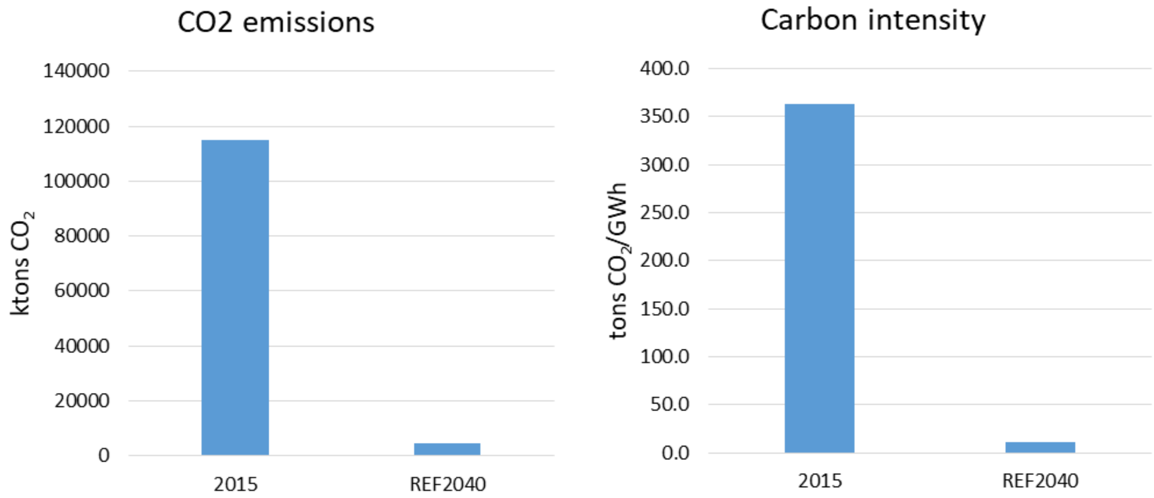


Figure 44: CO_2 emissions and carbon intensity of power generation for 2015 and 2040 of the Iberian Peninsula electricity system

The significant reduction in power generation from fossil fuels, aside from significantly reducing CO_2 emission also has a positive impact on the water dependence of the Iberian power sector, as both water withdrawal and water consumption decrease significantly (Figure 45). The water withdrawal in the Iberian Peninsula for 2015 is estimated[13] at over 12000Hm^3, while in 2040 projections show a drop to 3200 Hm^3, showing a 75% decrease. The drivers of this reduction are the phase out of the solid-fired plants and the reduction of the nuclear fleet. An additional driver, is the fact that all new power plants – operating in 2040 - are assumed to use wet-recirculating cooling systems, which has lower water withdrawal intensity, compared to the once-through cooling system used in the majority of the old plant fleet. However, this element has a significantly lower impact than the shifts in the power generation mix.

Water consumption follows the same trend with water withdrawal, dropping by 50% in 2040, compared to 2015. Despite the significant reduction, the decrease of water consumption is relatively lower compared to water withdrawal: this mainly stems from the assumption that the new power plants use wet-recirculating cooling system, having higher water consumption intensity, compared to the once-through technology. It must be noted that although a power plant equipped with wet-recirculating cooling system consumes almost the double amount of water, compared to a plant having once-through system, in order to produce the same amount of power, the former (wet-recirculating) withdraws forty times less water compared to the latter. In this sense, the wet-recirculating system, although consuming a higher amount of water, enables limiting the excess heat from the thermal discharge[14]. Moreover, the increased penetration of solar-thermal plants in the Iberian Peninsula mix shows counter effects on the water consumption reduction.

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13 The water withdrawal and consumption is estimated based on the methodology of section 1 for both 2015 and 2040; data on true water consumption of power plants was not found to be publicly available by the consortium.

14 U.S. electric generating plants have moved toward cooling systems that reuse water, mainly because of environmental standards that seek to limit excess heat from the water that can damage fish and other wildlife (thermal discharge) and to limit damage to organisms trapped when water is withdrawn from a source (called impingement), https://www.eia.gov/todayinenergy/detail.php?id=14971

Climate scenarios results

As mentioned above, the current study examines two climate scenarios RCP 2.6 and RCP 8.5 each with three variants, based on the precipitation level: an average, a dry and an extreme–dry case. The reduction in water levels leads to a reduced potential for hydropower production, whereas the increased temperatures of water flows can lead to closures of nuclear capacity (Table 22) in order to comply with environmental regulations.

Table 22: Nuclear capacity availability due to water temperature constraints violation for the Iberian Peninsula [PRIMES-IEM].

Scenario Name	Available Nuclear Capacity (GW)	Occurrence (Days per year)
RCP8.5Average	6.48 (100%)	355
	4.83 (75%)	4
	3.18 (49%)	5
	2.11 (33%)	1
RCP8.5Dry	6.48 (100%)	345
	4.83 (75%)	14
	3.80 (59%)	4
	3.18 (49%)	1
	2.11 (33%)	1
RCP8.5 ExtremeDry	6.48 (100%)	360
	4.83 (75%)	5

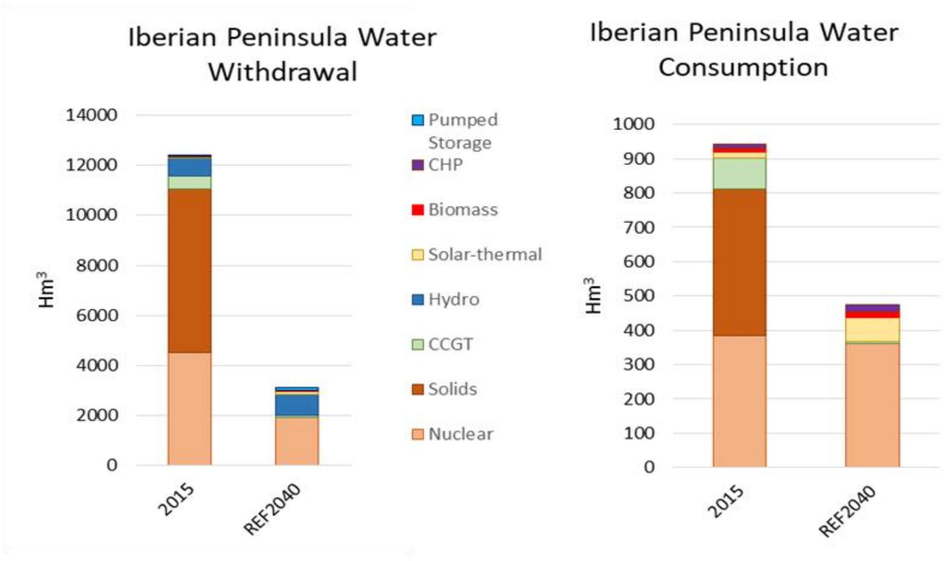

Figure 45: Water consumption and withdrawal for 2015 and 2040 Iberian Peninsula electricity system.

As shown in Figure 46 the reduced precipitation and streamflow on the rivers lead to a decrease of the hydropower generation, ranging from 16% to 18% and from 32% to 59% for the RCP 2.6 and RCP 8.5 scenario respectively, compared to the 2040 reference case. In addition, the significantly higher water temperature in the RCP8.5 climate scenario, as projected by the results of the HBV hydrological model, leads to the shutdown of some nuclear power, as shown in Table 22 for all the scenario specific variants. In the case of RCP 2.6 scenario variant, the water temperature increase is less intense; thus, the nuclear capacity remains the same, compared to the 2040 reference case.

Figure 46 presents the difference of the power generation mix and the system marginal price in the climate scenarios, compared to the 2040 reference case. The installed CCGT fleet, used merely for balancing purposes in the reference case, covers the decreased hydropower generation. In the RCP 2.6 extreme dry variant and all the variants of the RCP 8.5, load cuts occur as a result of the significant hydropower generation decrease and the nuclear power plants shut down, leading thus to a considerable increase of System Marginal Prices (SMP).

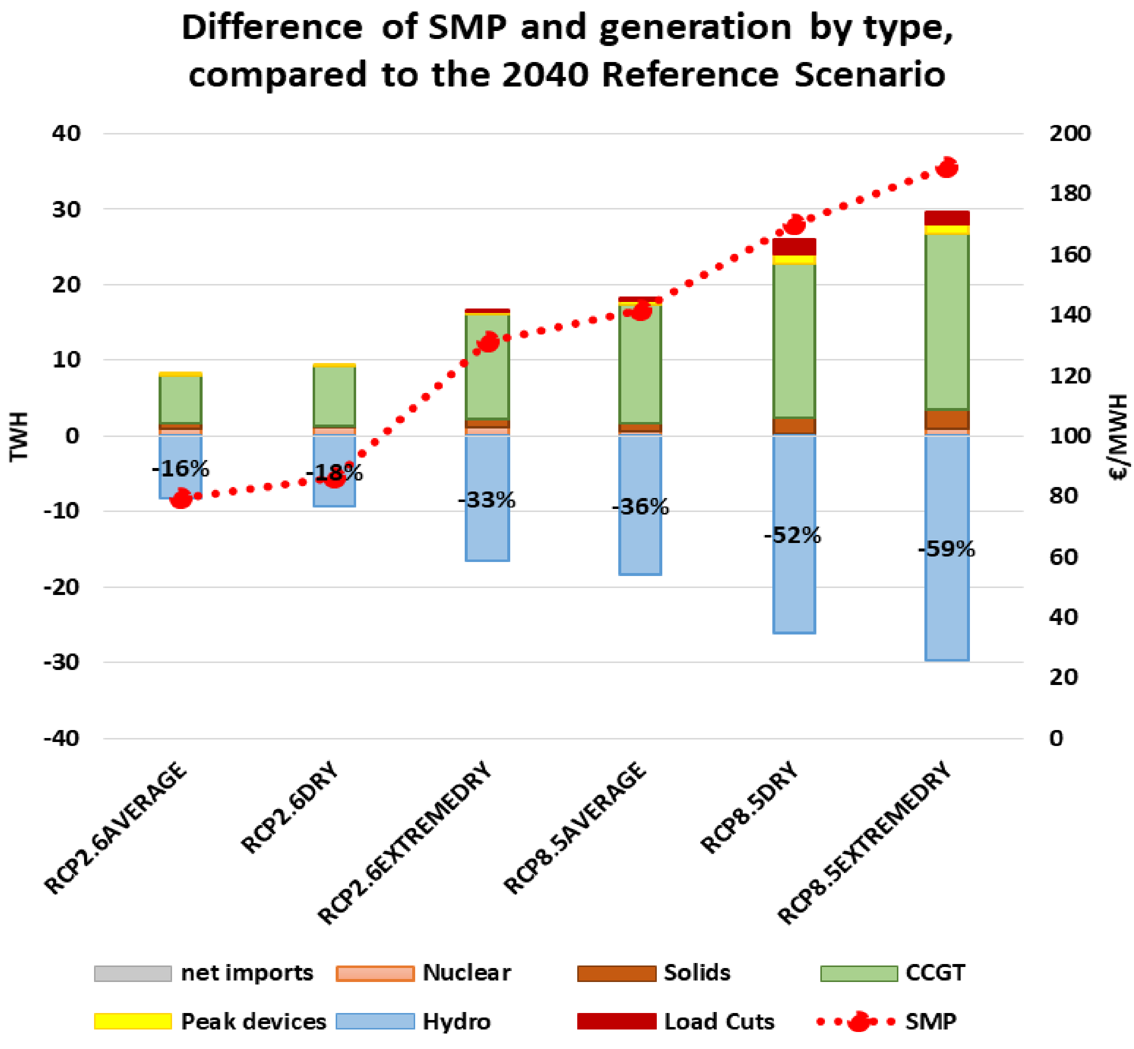

Figure 46: Difference of SMP and power generation by type, compared to the 2040 Reference Scenario for the Iberian Peninsula [PRIMES-IEM].

The average System Marginal Price (SMP) (Figure 46) of the Iberian Peninsula is heavily dependent on the generation from hydroelectric power plants. As the power generation from hydro power plants decreases, when moving to drier scenarios, the power generation from CCGT and solids power plants increases and even load cuts occur, as the installed capacity is not sufficient to cover the load, thus, resulting in much higher SMP. In extreme cases the observed load cuts drive the average SMP even higher, reaching an increase of almost 190 €/MWh in the worst-case scenario (RCP8.5 Extreme-dry) when compared with the 2040 Reference Scenario.

In order to shed further light in the results at an intra – regional level, Figure 47 disaggregates the results for the individual countries of the Iberian Peninsula. Portugal is covering the decreased hydroelectric generation with an increase of net electricity imports, coming from Spain, and the power generation from peak devices to a lesser extent. On the other hand, Spain increases the power generation from CCGT and solids power generation to cover the reduction of hydro power plants generation. In Spain the increase of CCGT and solids power generation is higher than the reduction of hydropower generation, due to the increase of net electricity exports in order to cover the reduced hydropower generation in Portugal. In extreme climate condition scenarios (RCP2.6 Extreme-dry, RCP8.5 Average, RCP8.5 Dry, RCP8.5 Extreme-dry) where high water temperatures result to shutdown of nuclear capacity, load cuts are observed for Spain and as a consequence in Iberian Peninsula (0.008% of electricity demand for RCP2.6 Extreme-dry, 0.091% of electricity demand for RCP8.5 Average, 0.487% of electricity demand for RCP8.5 Dry and 0.377% for RCP8.5 Extreme-dry scenario).

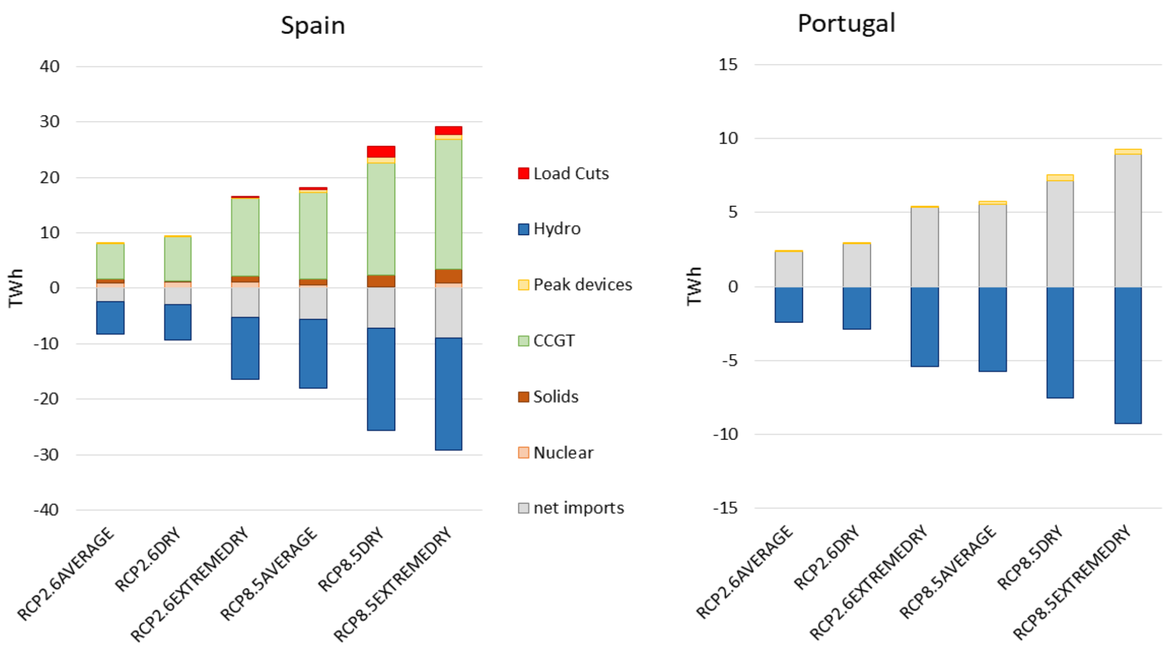

Figure 47: Difference of power generation per plant type for each scenario when compared to 2040 Reference Scenario (REF2040) [PRIMES-IEM].

The water withdrawal and water consumption in the Iberian Peninsula, for all scenarios, is presented in Figure 48. The total water withdrawn remains almost stable among all scenarios. The amount of water withdrawn from hydroelectric power plants drops, as a result of the reduced water availability and therefore power generation from hydroelectric power plants, and is shifted towards the respective amount of CCGT and solids power plants in correspondence with the trend of power generation. Consequently, the water withdrawal intensity is also stable around the level of 8 m^3/MWh as presented in Figure 49. On the other hand, the increasing share of CCGT and solids generation, which consume water in their cooling systems, unlike hydro power plants is responsible for the increased total water consumption in the Iberian Peninsula. The increase of total water consumption in the RCP8.5 Extreme-dry scenario reaches 16% when compared to the 2040 Reference scenario. The water consumption intensity is also increased, in proportion with the total water consumption, and reaching 1.42 m^3/MWh on the RCP8.5 Extreme-dry scenario. This implies that in an extreme dry scenario there will be increasing demand of water from the power system further exacerbating the limited water resources; the effects on other economic sectors have not been analysed in this study.

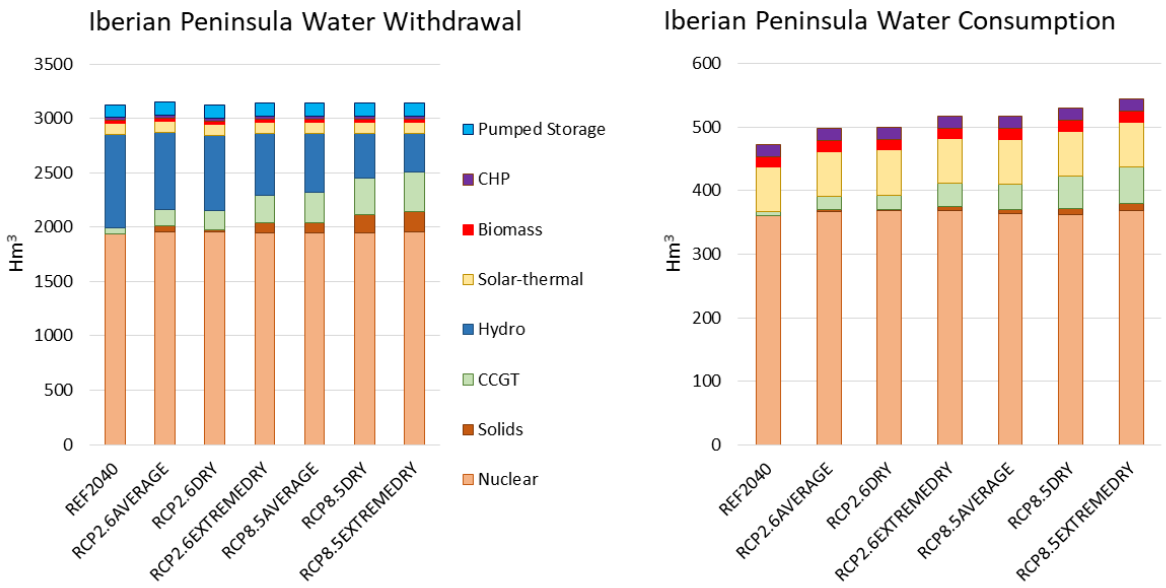

Figure 48: Water withdrawal and water consumption in the Iberian Peninsula[PRIMES-IEM]..

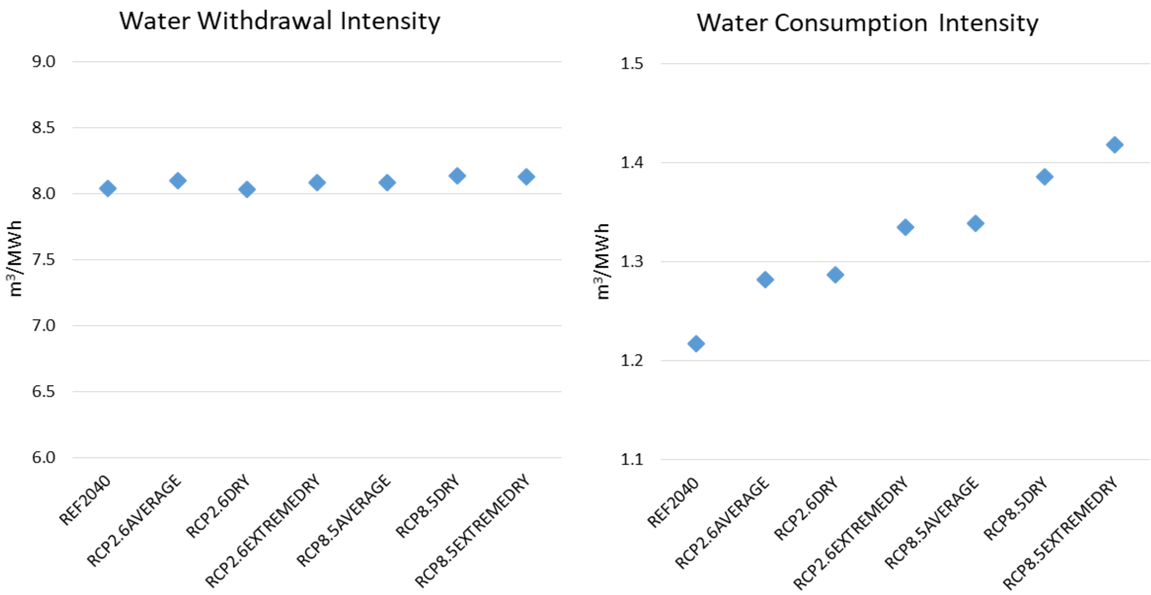

Figure 49: Water withdrawal and water consumption intensity of power generation in the Iberian Peninsula [PRIMES-IEM].

As it was expected, the utilisation factor of hydroelectric capacity drops as we move towards drier scenarios due to more arid climate conditions which result to lower streamflow on the rivers as shown in Figure 50. On the other hand, the utilisation factor of solids, CCGT and Peak Devices is increased, as those types of power plants take the burden of covering the gap in the power generation mix that is caused by the reduced hydroelectric and nuclear power generation. Nuclear utilisation factor remains almost stable and slightly lowering when there are nuclear power plants shutdowns due to high water temperature.

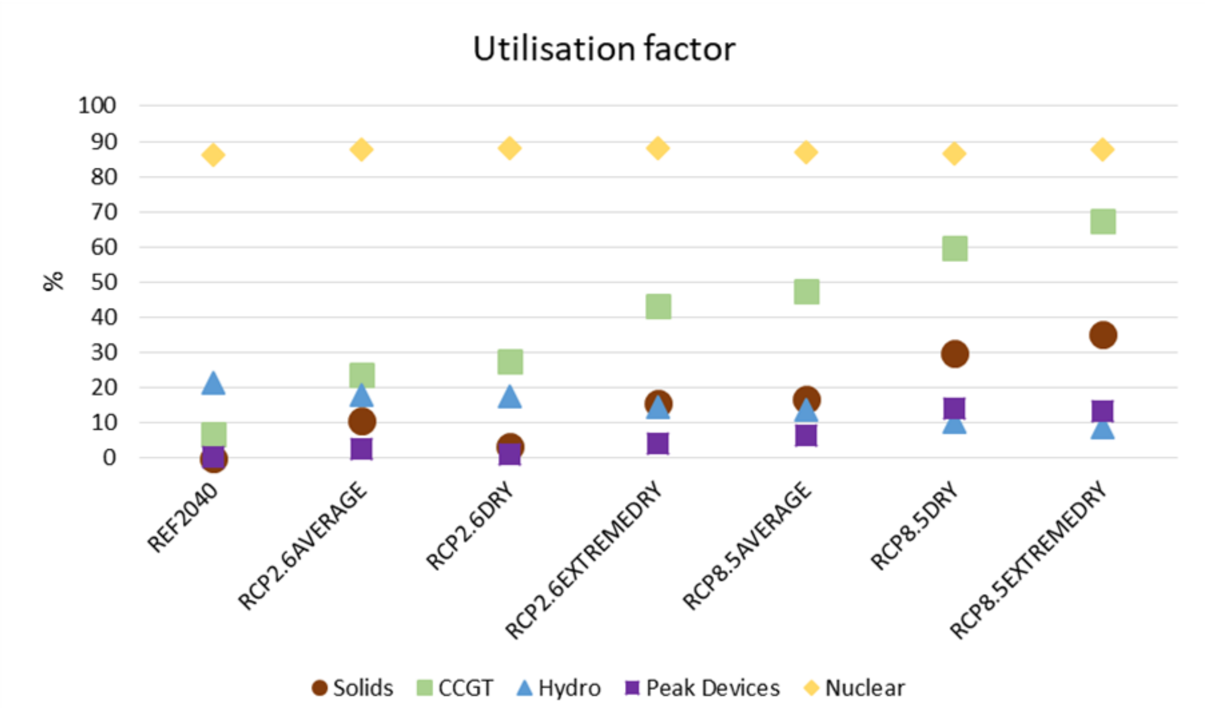

Figure 50: Utilisation factor by plants type (only plant types that are affected by different climate conditions) for the Iberian Peninsula. [PRIMES-IEM]

As climate conditions become drier, natural gas increasingly contributes to the power generation mix, with coal also increasing its output to a more limited extent (Figure 51). Waste and biofuels remain stable among the climate conditions scenarios because they have exhausted their potential (already in the 2040 EUCO Reference scenario).

As a consequence of the increased fossil fuel consumption, the total CO_2 emissions greatly increase among the scenarios and almost quadruple in the driest scenario (RCP8.5 Extreme-dry) as shown in Figure 52. The carbon intensity follows exactly the same trend and increases from 11.3 tons CO_2/GWh on the 2040 Reference scenario to 40.6 tons CO_2/GWh on the RCP8.5 Extreme-dry scenario, however much below current levels.

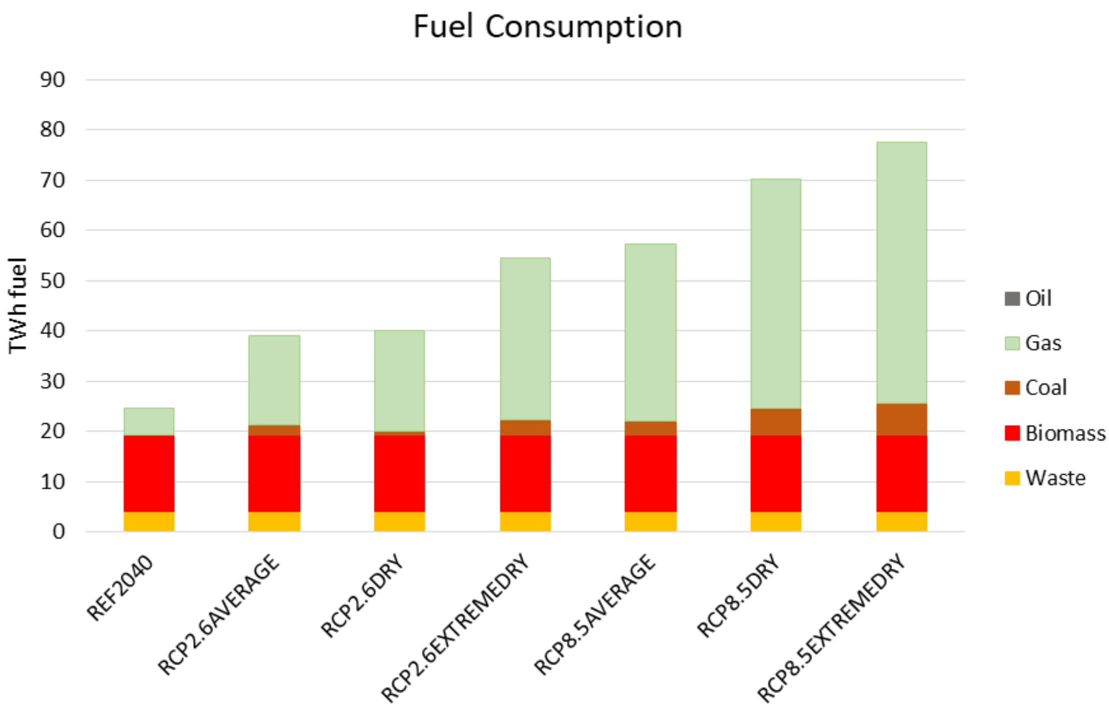

Figure 51 : Fuel consumption for power generation per fuel type for the Iberian Peninsula. [PRIMES-IEM]

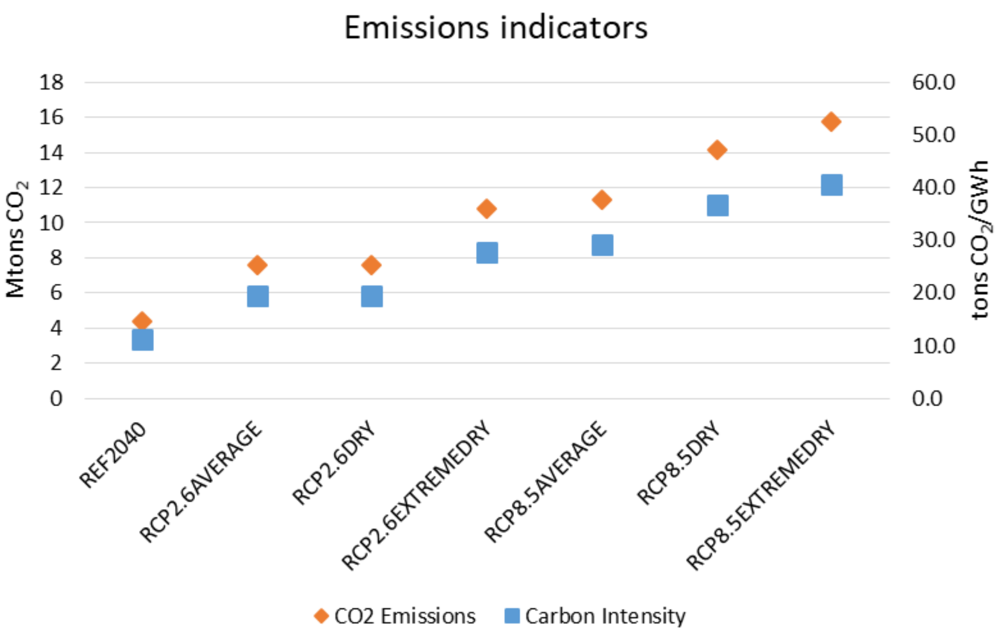

Figure 52: Total CO_2 emissions and carbon intensity of power generation for the Iberian Peninsula. [PRIMES-IEM]

The total power generation costs increase as climate conditions become drier and drier. The introduction, in the power generation mix, of power plants that are higher in the merit order in combination with load cuts[15] result into a dramatic increase in the total power generation cost, as shown in Figure 53, following the trend of the Average SMP.

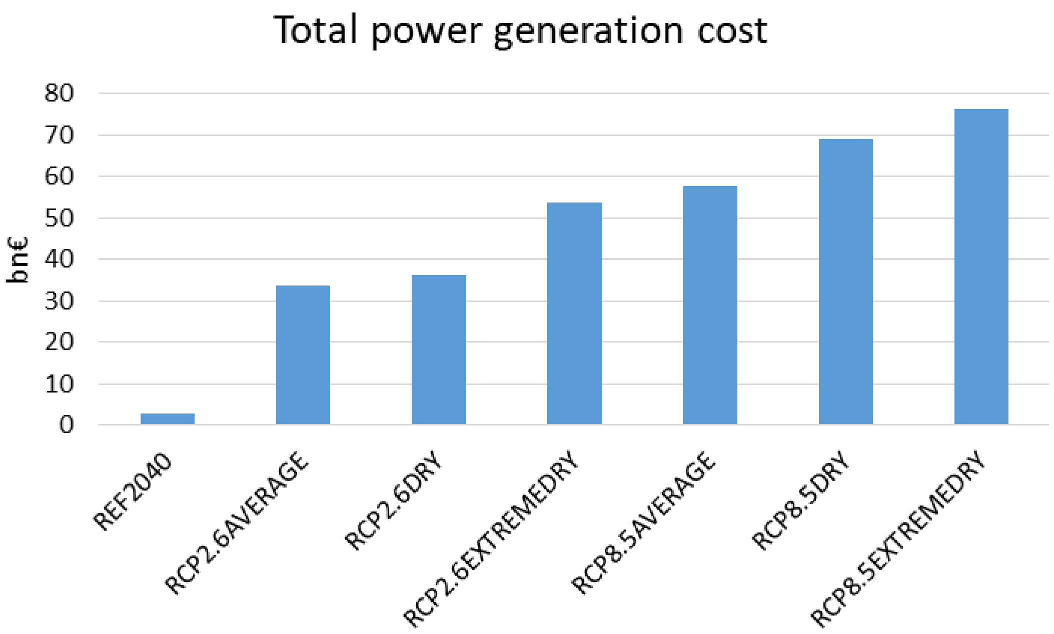

Figure 53: Total power generation cost for the Iberian Peninsula among all scenarios. [PRIMES-IEM]

Hydropower flexibility analysis

While in the energy systems analysis literature and practice flexibility is a well-established concept, in the water systems literature it is seldom used. To assess the additional flexibility that hydropower could contribute to the energy system, we formulated a flexibility metric that relies on the Capacity Inflow Ratio (CIR), i.e.

$$CIR = \frac{ReservoirCapacity}{Median(AnnualInflow)}$$

For example, in alpine watersheds, reservoirs are built with a capacity able to store more or less the average annual inflow in order to allocate it when the annual demand for energy or the energy prices are higher. Technically, this translates in that their storage to median annual inflow ratio is equal to one. Reducing water availability generally implies higher CIR values and, correspondingly, higher flexibility. Of course, lower availability also corresponds to less hydropower production/revenue, and it does not necessarily have a fully positive meaning. Yet, here we focus on operational flexibility and so the potential of hydropower for providing more services, such as load balancing which, ultimately, might become more valuable in a renewable energy dominated future than raw energy production.[16]

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[15] When load cuts occur the SMP becomes equal to the value of loss load (VOLL)

[16] https://www.ourenergypolicy.org/wp-content/uploads/2014/05/EPRI-Final-Report.pdf

In order to assess how this type of flexibility (i.e. the system controllability) will change in the future, the flexibility metric is formulated as:

$$F = \frac{CIR_{future}}{CIR_{history}}$$

If *F* value is larger than one, flexibility, will increase in the future. On the opposite, when *F* is smaller than one, the space for accommodating variations with respect to the average streamflow reduces and with it the flexibility of allocating energy production when it is more convenient/needed. With small *F*, dam operators will be more often force to spill, i.e. waste, water.

In the following flexibility maps (Figure 54), we report the value of *F* for each hydropower plant. Under the RCP2.6, all the Iberian Peninsula has a more controllable water system as water availability is in general expected to decrease. Under the RCP8.5, an increase in median annual inflow makes the system less controllable and flexible, especially in the northwest of the country. However, this may imply a higher production of energy to

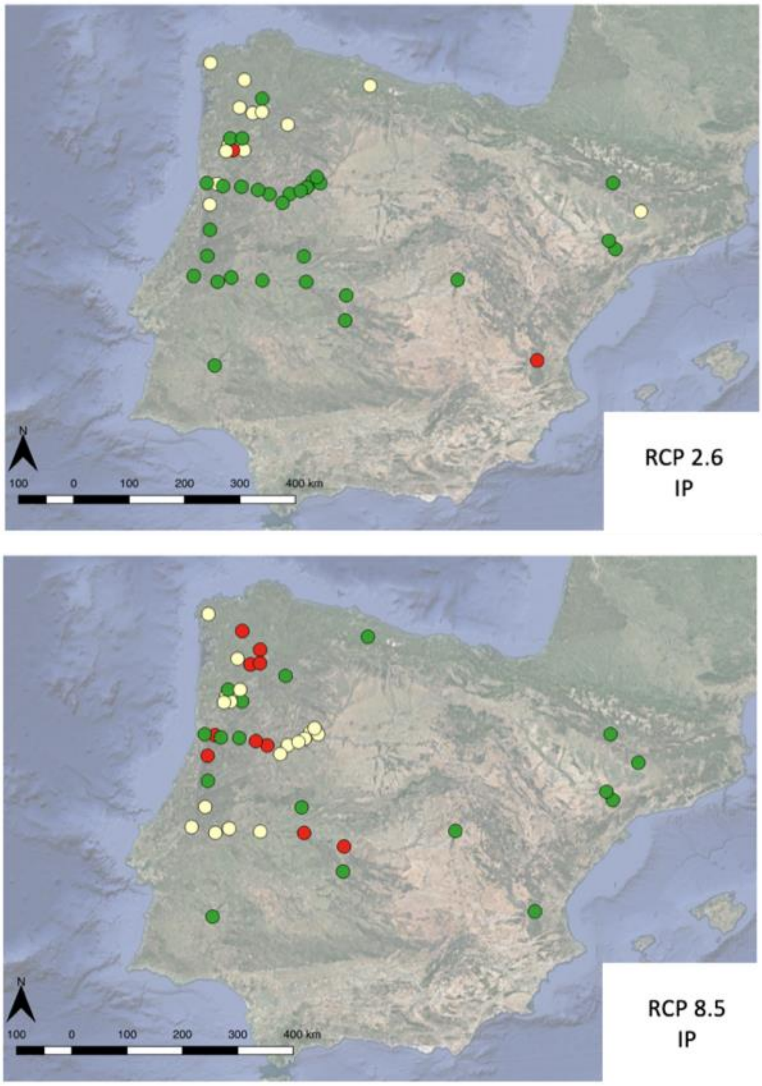


Figure 54: Flexibility maps for the Iberian Peninsula under RCP2.6 (top panel) and RCP8.5 (bottom panel). Green color represents more flexibility, red color represents less flexibility. Yellow dots show no significant change.

contribute to base load. Nonetheless, also under this scenario, the vast majority of the hydropower plants analyzed fall in the more flexible or no significant change condition - 34 in total - while only 10 will experience less flexibility.

5.2 Danube River Basin

Hydroclimatic analysis

As previously said for the Iberian Peninsula, temperature change is much larger under RCP8.5 than in RCP2.6. Moreover, it seems like the difference is more emphasized during wintertime with peaks larger than 5 °C, while it is reduced in the other seasons. For what concerns the precipitation, under RCP2.6 it seems like the Danube region will get wetter at the end of the century. On the other hand, under RCP8.5 a different pattern is observed, characterized by wetter winters and drier summers (Figure 55).

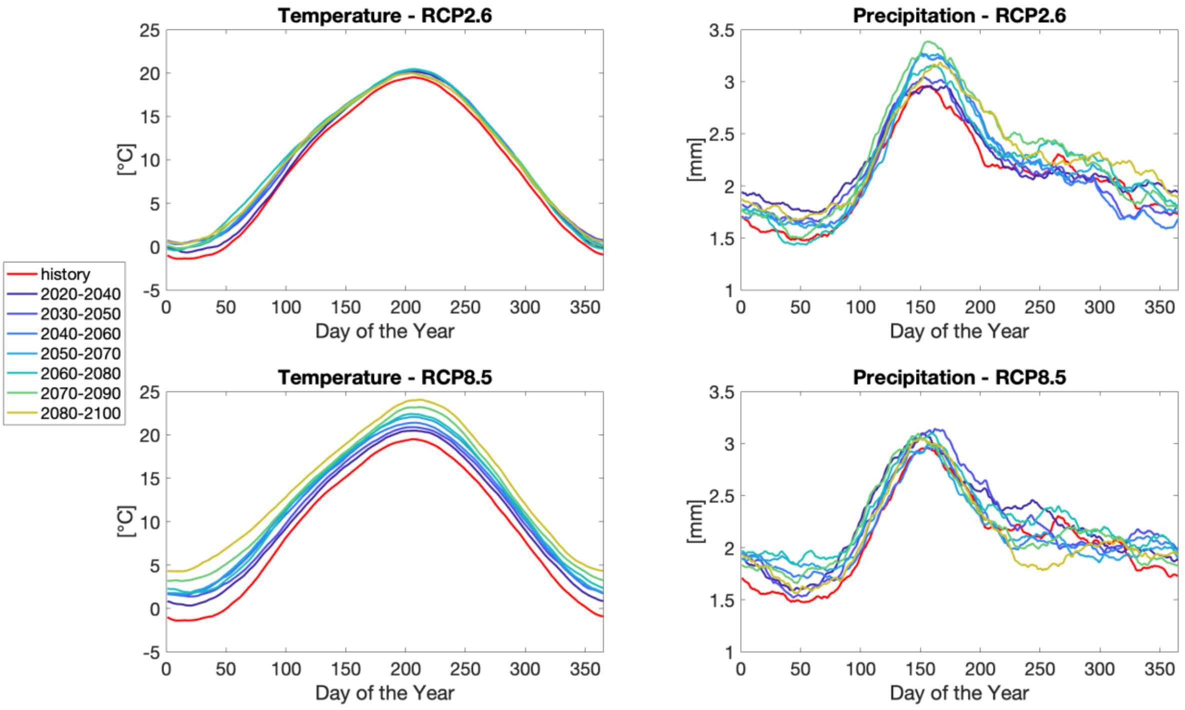


Figure 55: Danube region average temperature and precipitation projections under RCP2.6 (top panels) and RCP8.5 (bottom panels) scenarios. The color of the lines shows the time period considered in order to describe the evolution in time of these variables. The lines reported are the cyclostationary average over the time period considered.

Table 23: Average annual temperature and precipitation for Danube region: historical conditions (1984-2004), RCP 2.6 (2040-2060) and RCP 8.5 (2040-2060).

	1984 - 2004	RCP2.6 (2040-2060)	RCP8.5 (2040-2060)
Temperature [°C]	9.1	10.3	11.6
Precipitation [mm/y]	758	784	782

Considering the period analyzed using the energy models, the average annual temperature and precipitation for the historical period and future conditions at 2040-2060 under both RCPs are reported in Table 23.

In Figure 56 the cumulative distribution of annual precipitation for the Danube region is reported. Under the RCP2.6 scenario precipitation is more abundant than historical one: the minimum is larger, they agree on the same values for cumulative probability values between 0.1 and 0.4 but then it departs substantially from the historical distribution. Under RCP 8.5 the same holds, but more variability is observed, i.e. more differences at the high and low extreme.

Considering the 25th percentile over the control period as an average dry year, we can also conclude that the probability of such events is going to increase of only 1% and 4% under RCP 2.6 and RCP 8.5 respectively.

Historically, annual precipitation was distributed between 700 and 800 [mm/y]. On the whole, it increases under both RCP 2.6 and RCP 8.5. RCP 8.5 shows a quite flat distribution over the range 600 – 1000 [mm/y] while RCP 2.6 is centered around 700-900 [mm/y] and has higher extreme values. This can be seen in the histograms in Figure 57.

Figure 56: Empirical cumulative distribution of annual precipitation over the Danube region for control period (blue) , RCP 2.6 (yellow) and RCP 8.5 (red) over the time-span 2040-2060. Black dashed line intersects the median, while the red dashed one intersects the 25th percentile.

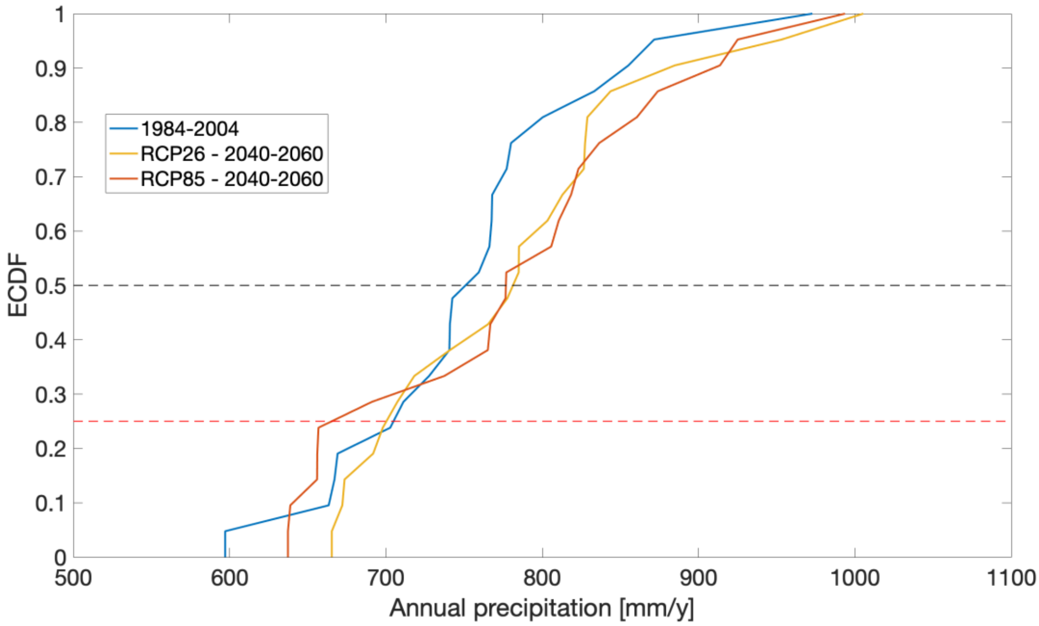
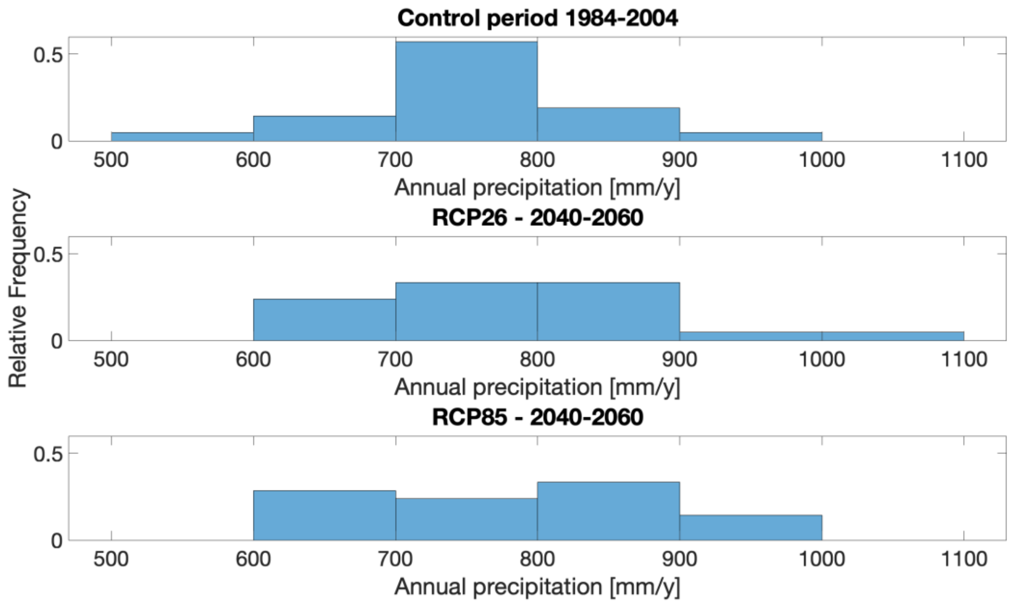


Figure 57: Histogram of annual precipitation over the Danube region for control period (top), RCP 2.6 (middle), RCP 8.5



(bottom).

As previously done with the Iberian Peninsula, the major basins (Figure 58) are analyzed in more detail to assess the spatial variability of climate change impacts over the Danube region. In Figure 59 temperature and precipitation are reported: the increase in temperature is evenly distributed, while precipitation changes accordingly to an east-west pattern where probably the dominant factor is the influence of Atlantic Ocean. Indeed, basins from the south or the east will get less precipitation under RCP8.5 rather than with RCP2.6. For many basins in the west, especially close to the Alps, an inverted trend is observed. Figure 60 shows the streamflow projections for the same basins, which are largely influenced by the heterogeneous precipitation patterns. Reduced streamflow is projected except for some areas in the west under RCP8.5, with more relevant impacts in south and east basins under RCP8.5.

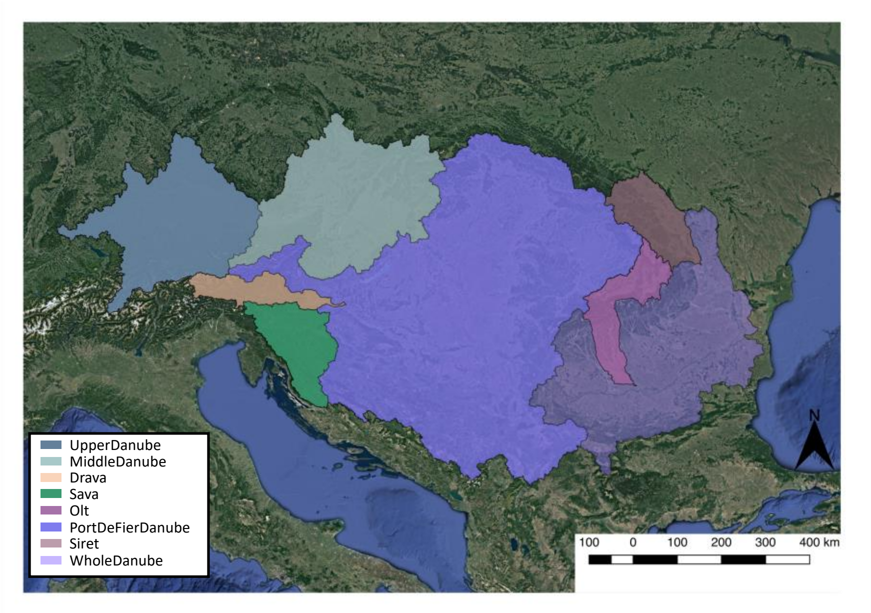


Figure 58: Basins analysed to evaluate spatial heterogeneous effect of climate change in the Danube region. Smaller basins are used as proxy to evaluate effect on whole basins.

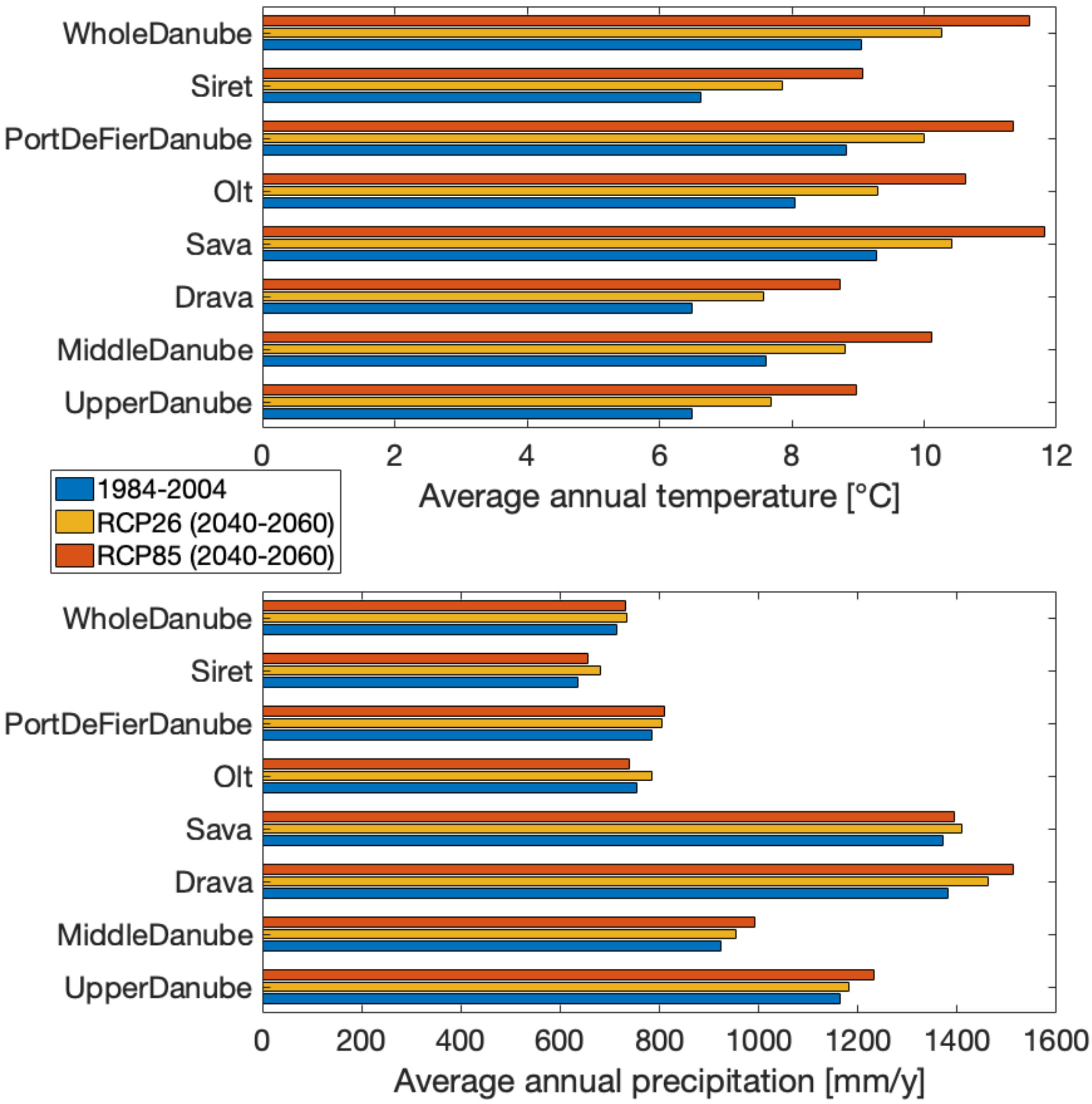


Figure 59: Average annual precipitation and temperature over the main river basins in the Danube region. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow, RCP8.5 2040-2060 in red.

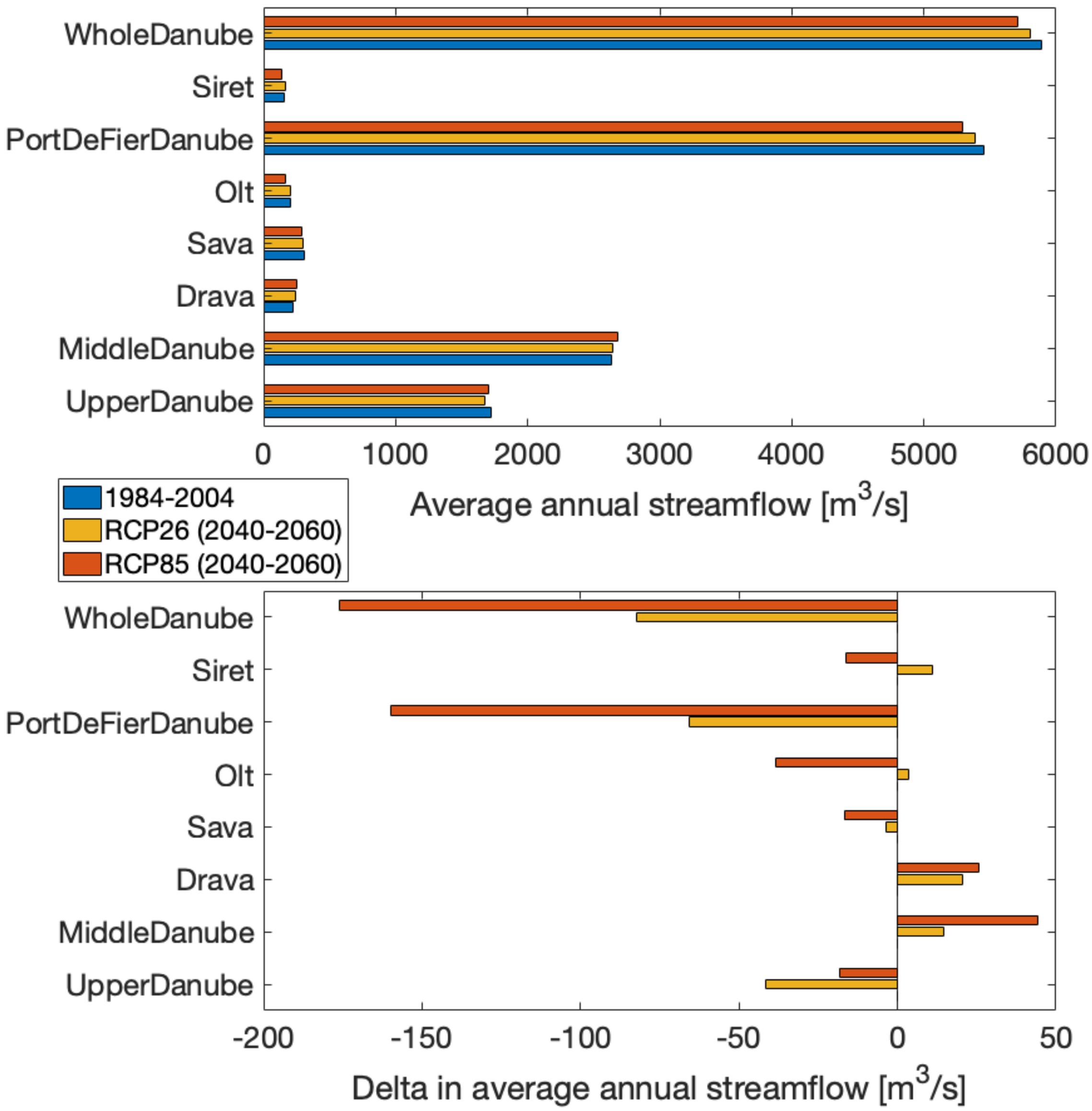


Figure 60: Average annual streamflow and its delta with respect to historical conditions over the main river basins in the Danube region. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow, RCP8.5 2040-2060 in red.

As the variability of the impacts can be appreciated using the sub-basin analysis, it is easy to imagine that it can be even larger considering the single power plants. As an example, in Figure 61 streamflow trajectories are reported for the Gabcikovo power plant. RCP2.6 will result in no change in the short period, while at the end of century the streamflow average and its distribution in time will look more abundant, especially from November to March. Under the RCP8.5 scenario, different effects occur in time. In the period 2040-2060 a large increase in wintertime streamflow and a trajectory not far from the historical one in the other months can be observed. At the end of the century, the streamflow does not depart substantially from the historical one, but it is more constant through the year, with a single peak around summer months.

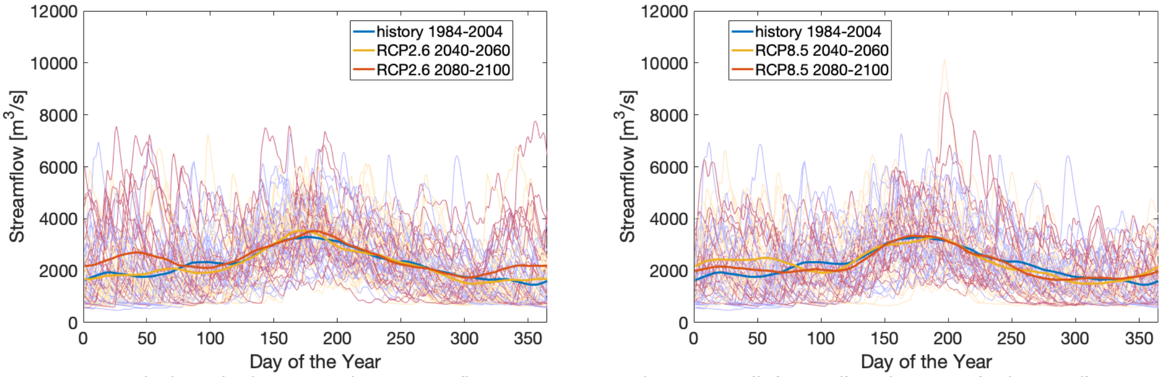


Figure 61: Gabcikovo hydropower plant streamflow projections under RCP2.6 (left panel) and RCP8.5 (right panel) scenarios. The color of the lines refers to different time intervals. The faded thin lines in the background show each single year streamflow trajectory for the period considered while the thicker ones represent the cyclostationary average over the period.

Comparison between the 2015 and 2040 energy systems based on the EUCO30 scenario.

The electricity system of the Danube River Basin for 2015 is strongly dependent on thermal and nuclear power generation, with those two types of power generation covering over 50% of the power generation mix, while variable renewables (wind-onshore, wind-offshore, solar, etc.) and hydroelectric power generation cover roughly one third of the total power generation as shown in Figure 62. On the other hand, under the EUCO projection for the electricity system of the Danube River Basin for 2040, hydro and variable renewables cover 50% of the power generation mix, while thermal and nuclear power plants still cover a substantial share, over 45%. The largest decrease in power generation is observed for solids, due to the assumed high ETS prices, resulting in solid power generation covering only 4% of total power generation for Danube River Basin in 2040 compared to 28% in 2015; the shares and absolute generation from nuclear and CCGT increase in 2040 compared to 2015.

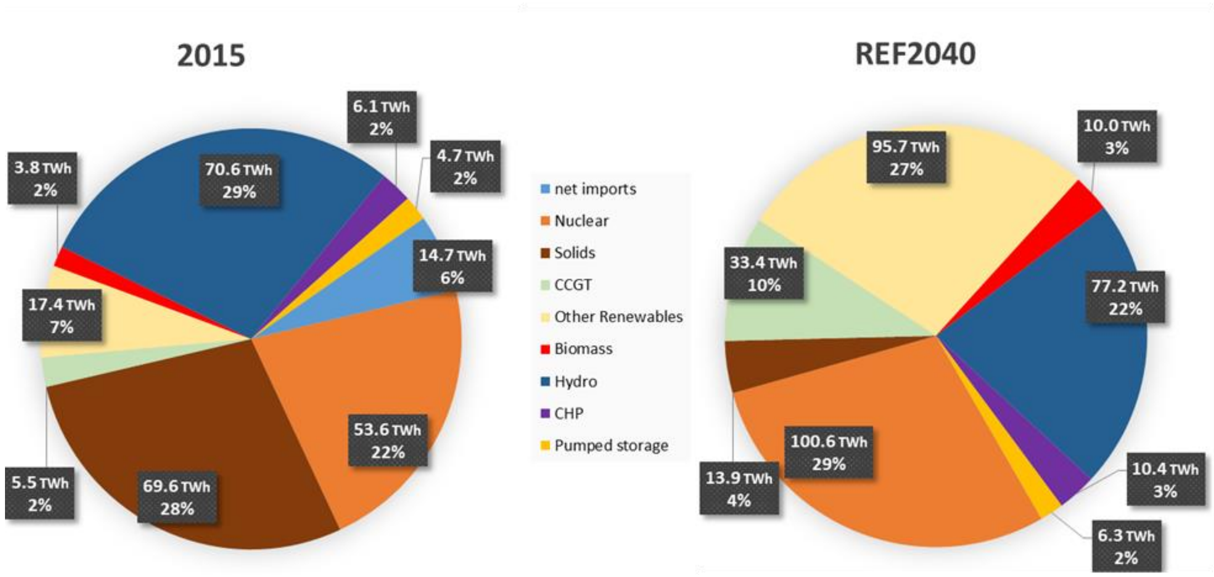


Figure 62: 2015 and 2040 power generation mix of the Danube River Basin region. [PRIMES]

The decarbonisation context under the EUCO projections for the Danube River Basin electricity system can become clearer when looking at the CO_2 emissions in Figure 63. The total CO_2 emissions in 2040 are reduced by over 85% when compared to those of 2015. Carbon intensity also follows a similar trend and is reduced by 90%.

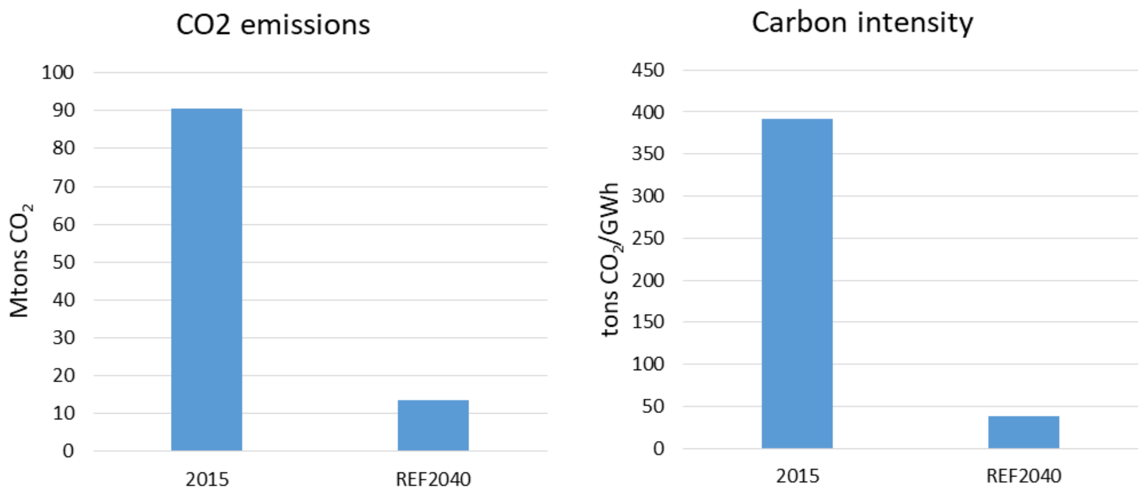


Figure 63: CO_2 emissions and carbon intensity for 2015 and 2040 of the Danube River Basin electricity system. [PRIMES-IEM]

In the decarbonisation context, the increased share of variable RES in the power generation mix of the Danube River Basin has a significant impact on the water withdrawal (Figure 64), resulting in a 20% reduction in 2040 compared to 2015. Even though power generation from nuclear power plants increases in 2040 when compared to 2015, the water withdrawal from nuclear power plants decreases because newly commissioned nuclear power plants are considered to be equipped with wet-recirculating cooling system, which has lower water withdrawal intensity compared to once-through cooling system that the majority of older nuclear power plants are equipped with. In addition, the phase-out of solids power plants from the power generation mix becomes evident as the water withdrawal from solids decreases greatly (Figure 64).

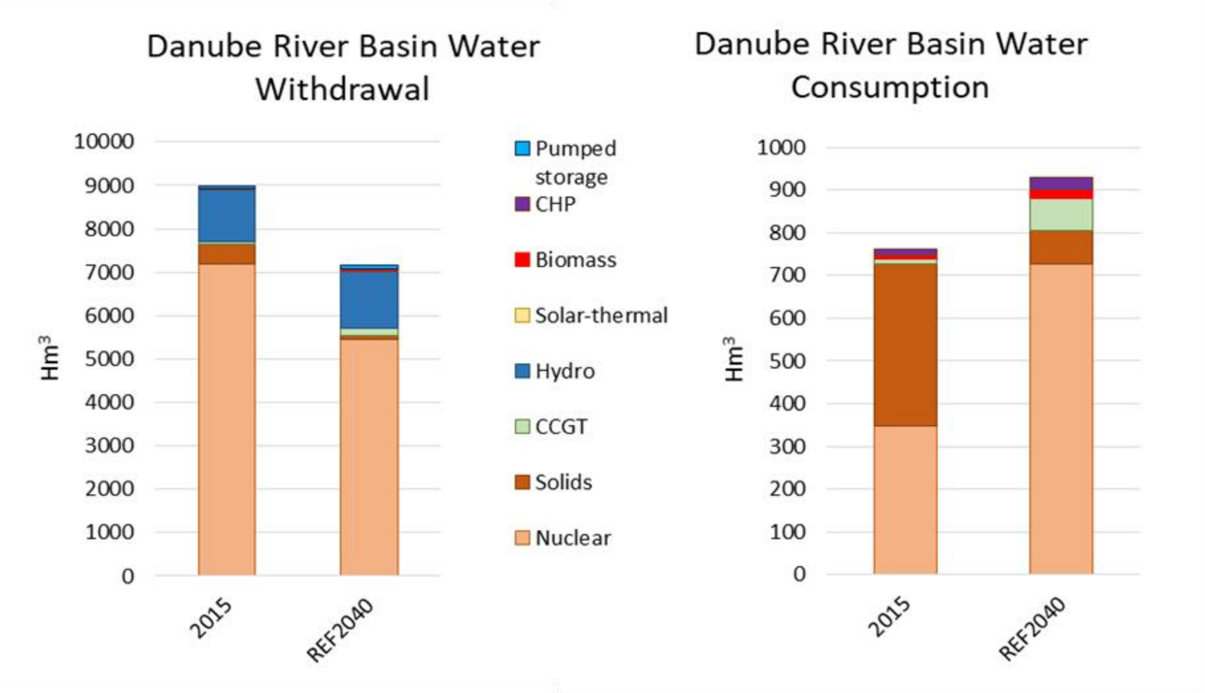


Figure 64: Water consumption and withdrawal for 2015 and 2040 of the Danube River Basin electricity system. [PRIMES-IEM]

On the contrary, a 22% increase in total water consumption in 2040 when compared to 2015 is observed for Danube River Basin. Even though the water consumption by solid power plants is drastically reduced the huge increase of water consumption by nuclear power plants, which is caused by the wet-recirculating cooling system of newly commissioned nuclear power plants, result in a higher amount of water consumed for cooling purposes in power generation. In addition, the water consumption of CCGT is also notably increased, as a result of the increased power generation from CCGT power plants.

Climate scenarios results

Following the same approach as the Iberian Peninsula, two climate scenarios RCP 2.6 and RCP 8.5 each with three variants, based on the precipitation level were quantified: an average, a dry and an extreme –dry case were examined.

The Danube River watershed is characterised by snow dynamic. For this reason, the water discharge does not only depend on precipitation but also depends on the ambient temperature, which determines the amount of snowmelt. Since dry years were selected based on precipitation levels, it is reasonable that one scenario that is considered drier than the previous might present higher hydroelectric power generation (e.g. RCP2.6 Average-RCP2.6 Dry), see Figure 65. A scenario with very high water temperatures was not analysed, although these might occur in the future. A scenario with extremely high water temperatures could lead to the shut-down of all nuclear and fossil plants in the region, which would exacerbate load cuts.

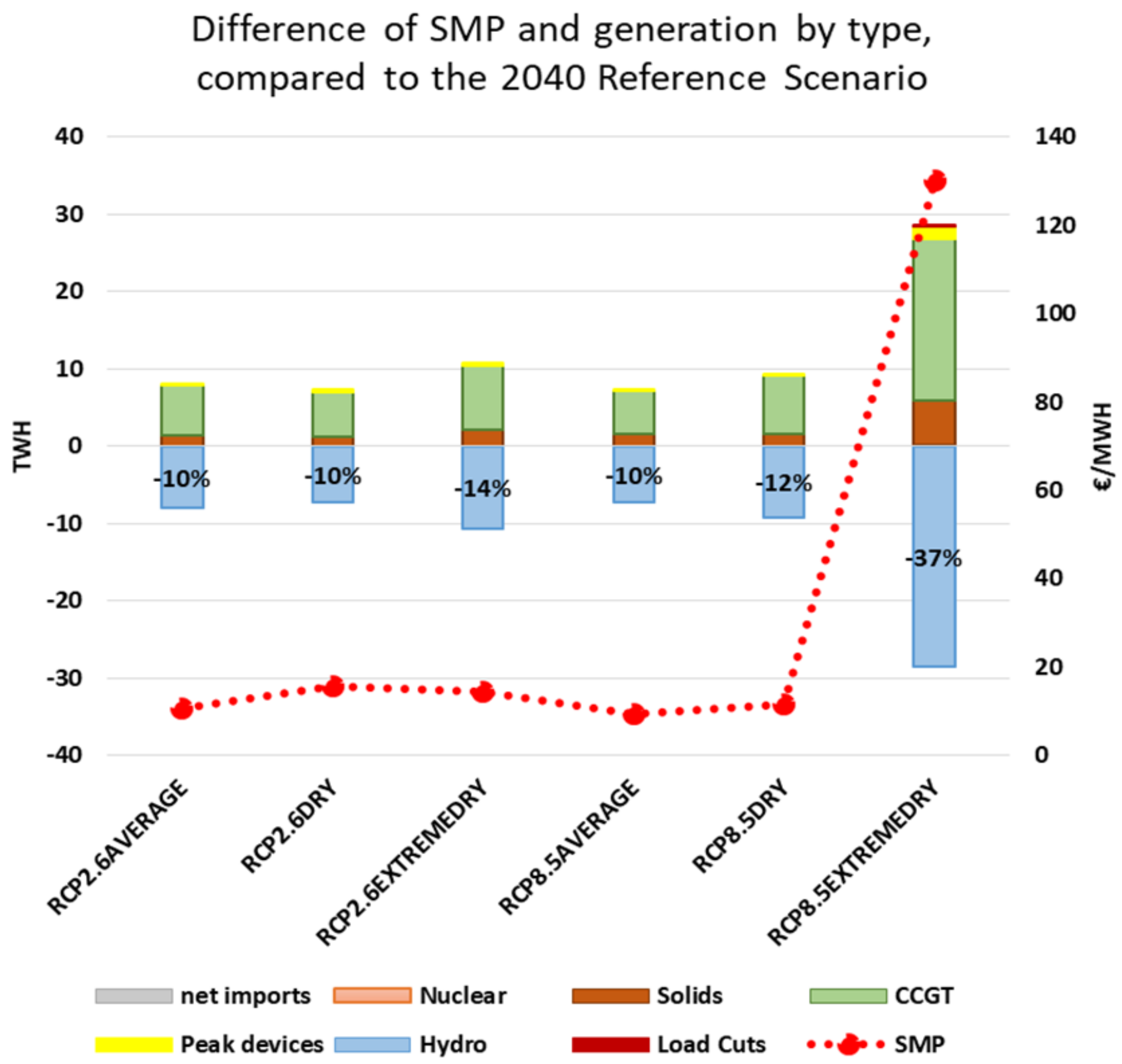


Figure 65: Difference of SMP and power generation by type, compared to the 2040 Reference Scenario (REF2040) for the Danube River Basin. [PRIMES-IEM]

As Figure 65 shows, the changed climate conditions have a much lower impact on the Danube River Basin, compared to effects in the Iberian Peninsula. Due to the snow dynamic, which characterizes the Danube watershed, small differences are presented among the majority of the scenarios. Besides RCP8.5 Extreme-dry, all other scenarios result to a 10%-14% reduction in hydroelectric power generation and in all those climate conditions, the CCGT power generation is mainly increased to cover the gap created by the decreased hydroelectric generation. This results in an increase of average System Marginal Price around 16 €/MWh.

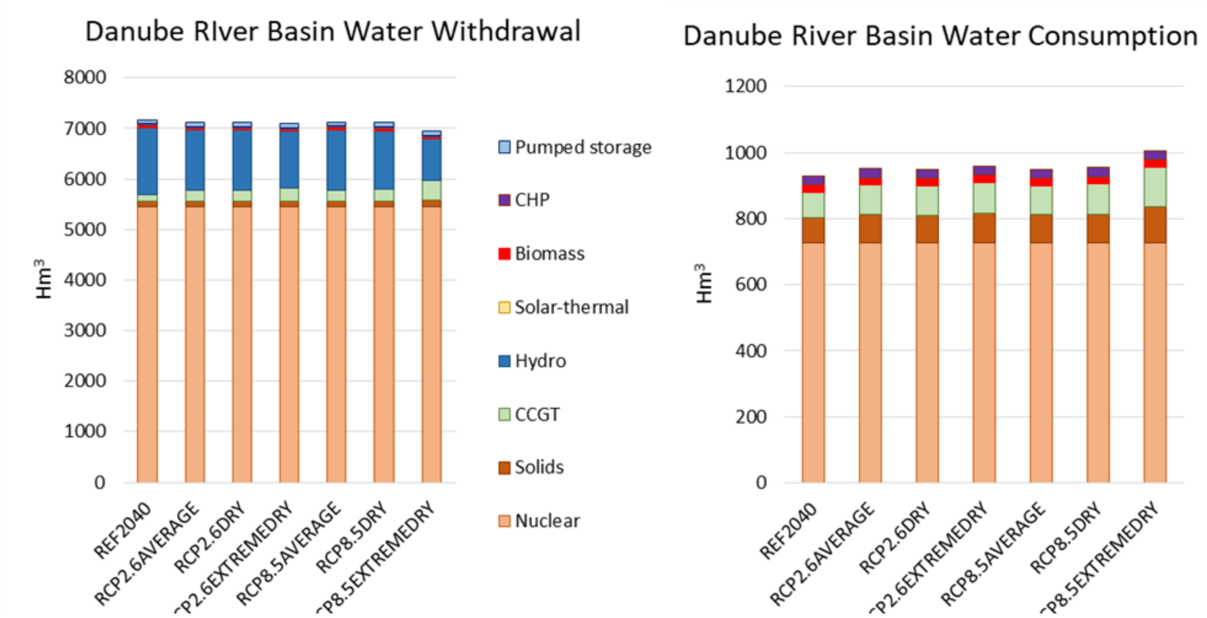


Figure 66: Water withdrawal and water consumption of power generation in the Danube River Basin. [PRIMES-IEM]

The extreme climate conditions (RCP8.5 Extreme-dry scenario) result in a 37% reduction of hydroelectric power generation in the Danube River Basin region. The electricity supply system responds by increasing the power generation from solids and CCGT power plants and peak devices but it is not enough to meet the demand, consequently load cuts are observed (approx. 0.1% of total demand). The increased power generation from solids, CCGT and peak devices as well as the load cuts drive the average System Marginal Price almost to 234 €/MWh, over 130 €/MWh higher than the 2040 Reference Scenario.

It is worth mentioning that in all climate scenarios, the streamflow of the rivers is more than enough so all thermal and nuclear power plants can operate. The same applies to the water temperature, which in none of the scenarios reaches or overtakes the environmental limits, thus does not affect the operation of thermal and nuclear power plants in the Danube River Basin Region.[17]

The water withdrawal and water consumption in the Danube River Basin for all scenarios are presented in Figure 66. The total amount of water withdrawn slightly decreases when moving to drier scenarios. This reduction in water withdrawal is explained by the fact that CCGT and solids power plants, which take the share of decreased hydroelectric power in the power generation mix, use wet-recirculating cooling systems, thus having lower water withdrawal intensity than hydroelectric power plants. As a result, the water withdrawal intensity is decreased from 20.64 m^3/MWh on 2040 Reference scenario to 20.12 m^3/MWh on the RCP8.5 Extreme-dry scenario as shown in Figure 67. On the other hand, the increasing share of CCGT and solids generation, which consume water in their cooling systems, unlike hydro power plants, to the power generation mix when moving to drier

[17] Situations like the 2004 drought are unlikely to have an effect as the power plant which was mainly affected – Cernavoda Nuclear power plant- has been since equipped with a changed water supply channel allowing it to operate even in drought/high temperature conditions.

scenarios is responsible for the increased total water consumption in the Danube River Basin. The increase of total water consumption in the RCP8.5Extremedry scenario reaches 9% compared to the 2040 Reference scenario. The water consumption intensity is also increased, in proportion with the total water consumption and reaching 2.91 m^3/MWh on the RCP8.5 Extreme-dry scenario.

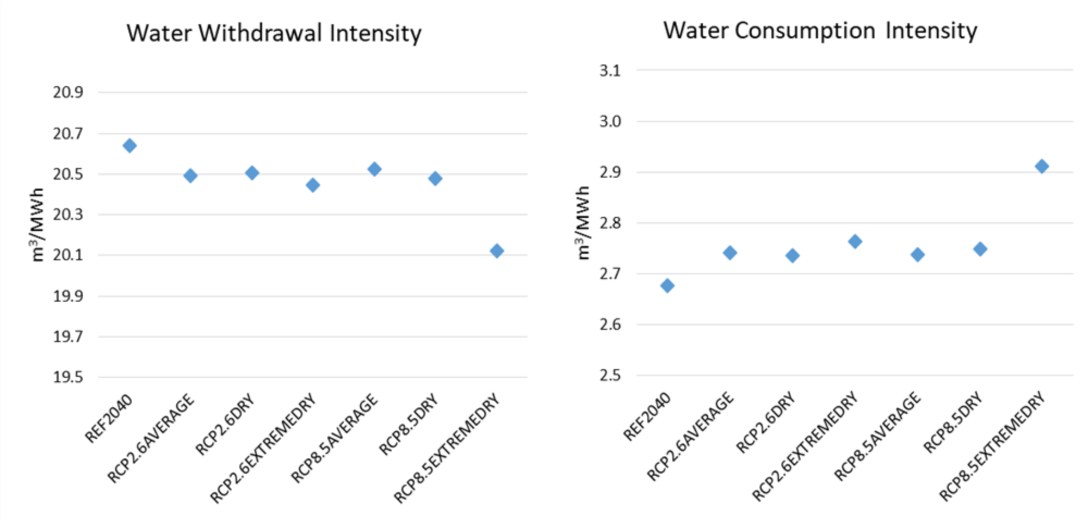


Figure 67: Water withdrawal and water consumption intensity of power generation in the Danube River Basin. [PRIMES-IEM]

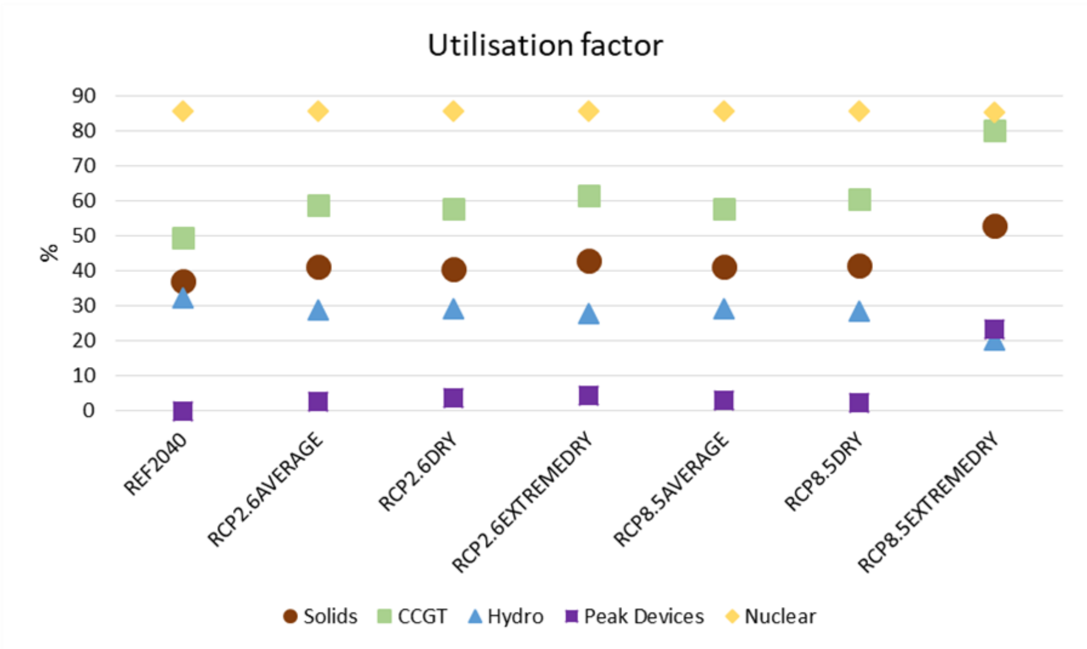


Figure 68: Utilisation factor by plants type (only plant types that are affected by different climate conditions) for the Danube River Basin. [PRIMES-IEM]

The utilisation factor of hydroelectric capacity, as can be seen in Figure 68, slightly drops as we move towards more dry scenarios due to more arid climate conditions which result in lower streamflow in the rivers, as is expected. On the other hand, the utilisation factor of solids, CCGT and Peak Devices is increased, as those types of power plants take the burden of covering the gap in the power generation mix. The nuclear utilisation factor remains stable because as mentioned above water temperature does not reach the environmental limits and nuclear power plants can, in all scenarios, be fully operative.

Fuel consumption by fuel type is shown in Figure 69 for all scenarios. CCGT and solids (coal and lignite) present an increased consumption as we move to drier climate conditions, as a result of their increased participation in the power generation mix due to the decreased hydroelectric power generation. In the driest climate conditions (scenario RCP8.5 Extreme-dry) the natural gas fuel consumption presents an increase of 70% when compared with the 2040 Reference scenario.

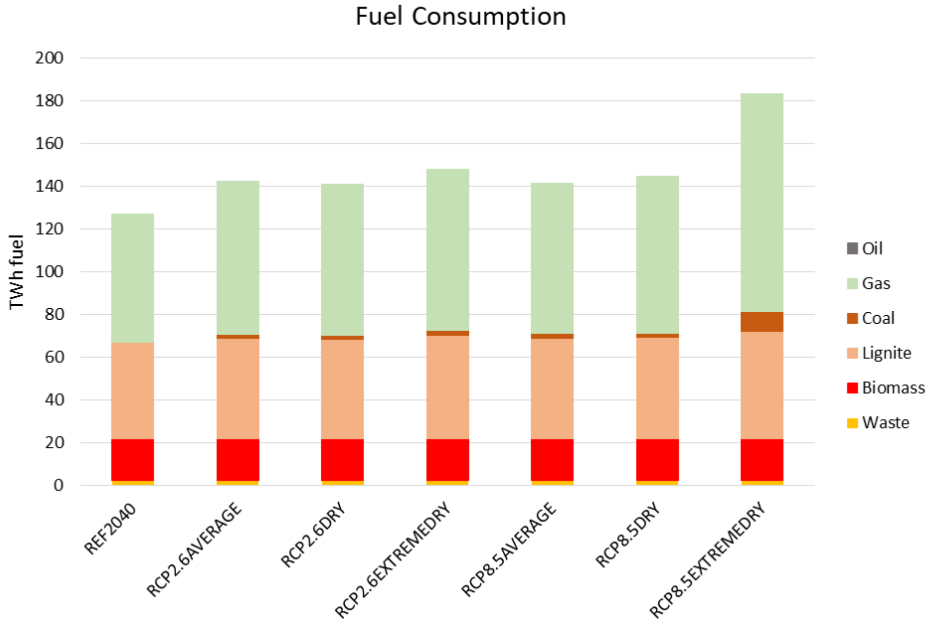


Figure 69: Fuel consumption for power generation per fuel type for the Danube River Basin. [PRIMES-IEM]

The increased use of fossil fuels for power generation, in order to cover the decreased hydroelectric power generation under dry climate conditions, results in increased CO_2 emissions as shown in Figure 70. Carbon intensity of power generation follows exactly the same trend, reaching 80 tons CO_2/GWh, when in 2040 Reference scenario is 38 tons CO_2/GWh.

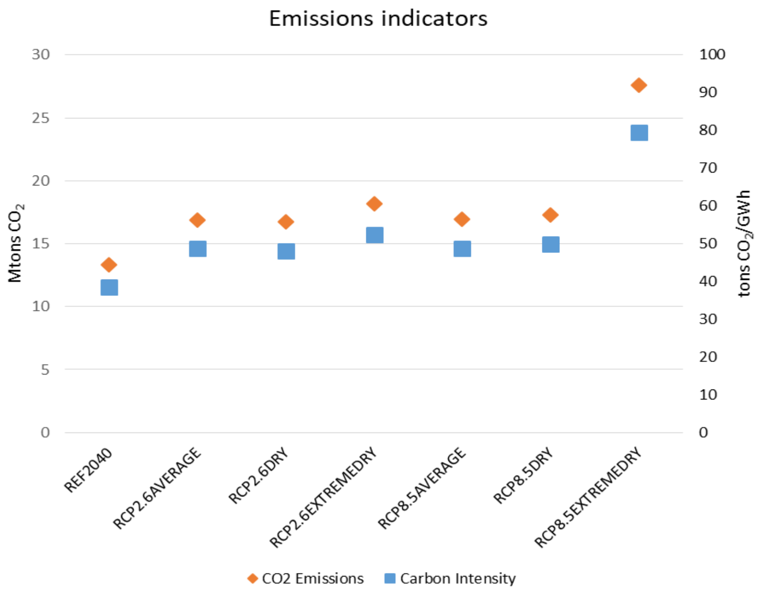


Figure 70: Total CO_2 emissions and carbon intensity of power generation for the Danube River Basin. [PRIMES-IEM]

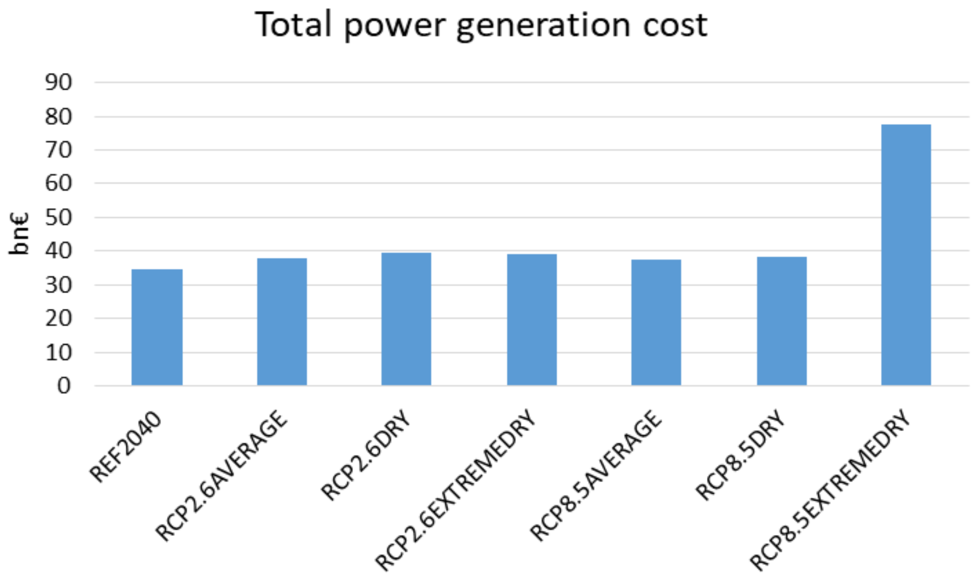


Figure 71: Total power generation cost for the Danube River Basin region among all scenarios [PRIMES-IEM]

As the climate conditions become drier and drier the total power generation cost is increased. The increased participation, in the power generation mix, of power plants that belong to higher merit order results to a huge increase of total power generation cost in the RCP8.5 Extreme-dry scenario, as shown in Figure 71.

Hydropower flexibility maps

Flexibility maps are shown for the Danube region in Figure 72. As previously said in 0, areas more depending on glacier melting will experience more average water availability, while basins far from the alpine area will experience less water flow. This can be clearly seen also in the maps below. Power plants located in alpine areas, or areas where the alpine influence is still heavy, are expected to have less controllable periods with a reduced flexibility. At the same time, where inflow is not mostly glacier and snow driven (north and north east green points) there will be more flexibility, meaning more ability to control the streamflow and timing of electricity generation.

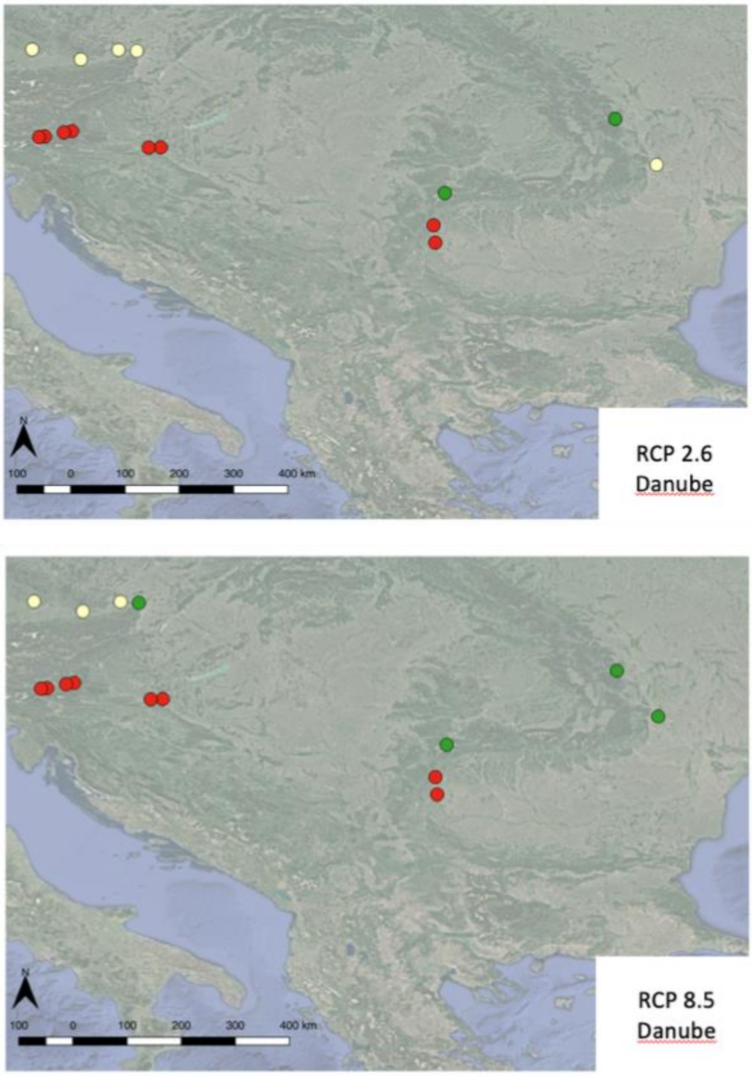


Figure 72: Flexibility maps for the Danube region under RCP2.6 (top panel) and RCP8.5 (bottom panel). Green color represents more flexibility, red color represents less flexibility. Yellow dots show no significant change.

5.3 Alpine region

Hydroclimatic analysis

Figure 73 summarizes the analysis of climate projections for the Alpine region. There is an increase in temperature both under RCP2.6 and RCP8.5 (much stronger effect), especially during the winter months. As for precipitation, an anticipation of the summer rain and an increase in precipitation occur in the first and last months of the year under RCP2.6. Under RCP8.5, the same anticipation of spring rain and a sharp decrease of rainfall in late summer are observed. As stated above for RCP2.6, the region is projected to get wetter during the first and last months of the year.

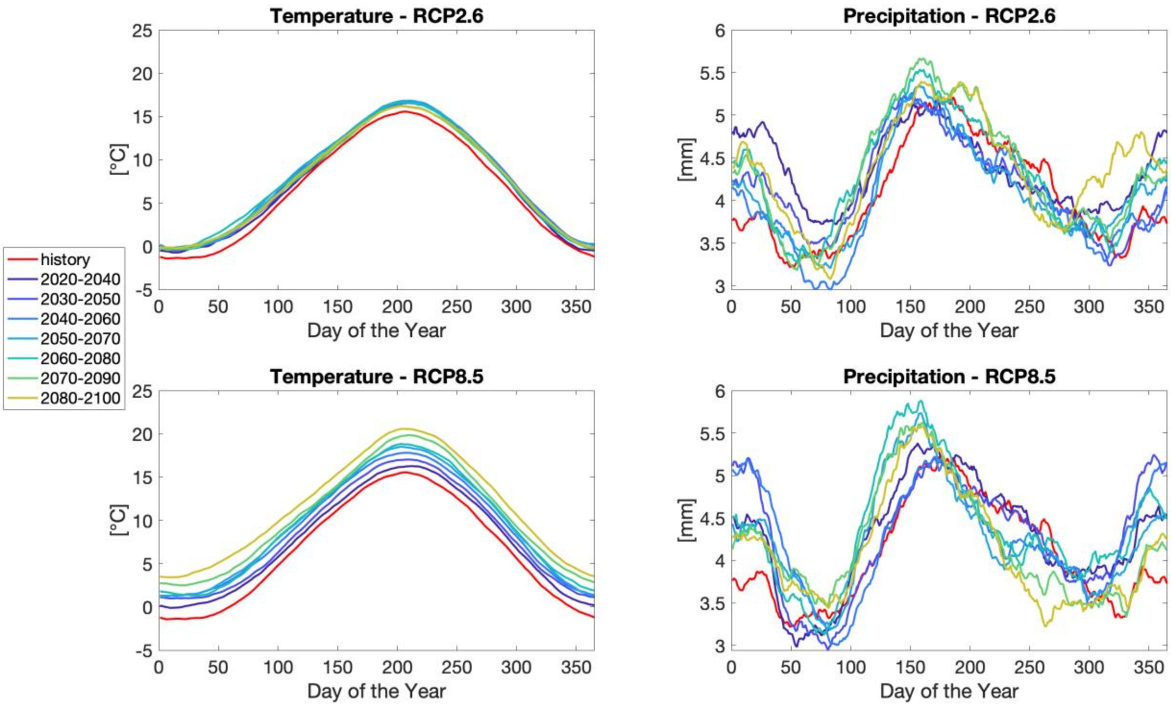


Figure 73: Switzerland average temperature and precipitation projections under RCP2.6 (top panels) and RCP8.5 (bottom panels) scenarios. The color of the lines shows the time period considered in order to describe the evolution in time of these variables. The lines reported are the cyclostationary average over the time period considered.

Average annual temperature and precipitation are reported in Table 24, according to the years analyzed more in detail in the project. Substantial increase in temperature occurs in both scenarios. Under RCP8.5 the region will get wetter while RCP2.6 won't have a significant impact on precipitation.

Table 24: Average annual temperature and precipitation for the Alpine region: historical conditions (1984-2004), RCP 2.6 (2040-2060) and RCP 8.5 (2040-2060).

	1984 - 2004	RCP2.6 (2040-2060)	RCP8.5 (2040-2060)
Temperature [°C]	6.6	7.8	9.1
Precipitation [mm/y]	1484	1468	1554

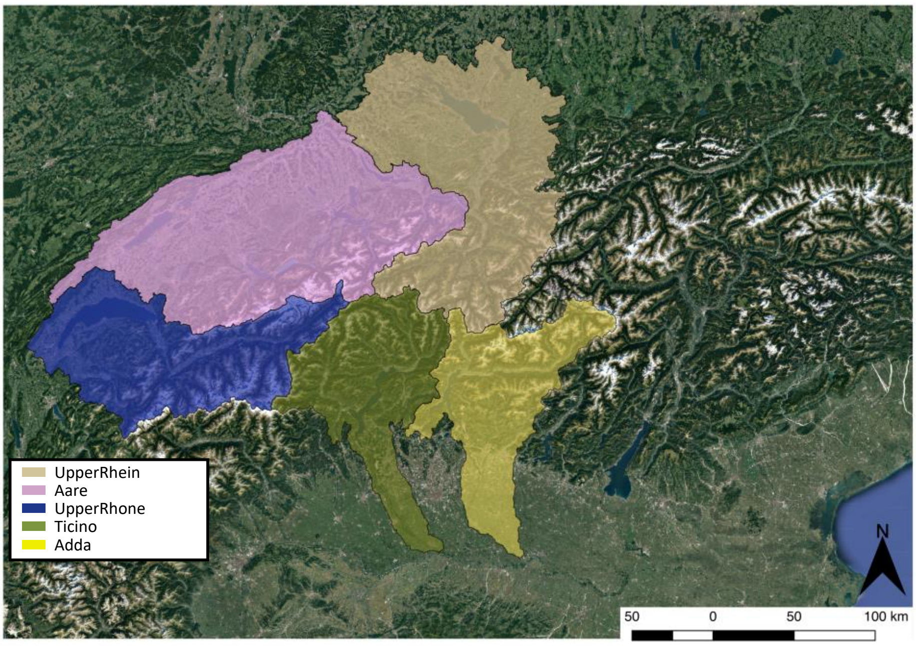


Figure 74: Basins analyzed to evaluate spatial heterogeneous effect of climate change in the Alps.

The Alps are not affected homogeneously in space by climate change. By considering information for the single major river basins interested by the analysis (Figure 74), a clear north-south pattern emerges. Indeed, while the temperature effect is homogeneous over the region, precipitation changes are opposite in southern and northern Alps: the north gets drier under RCP2.6 but wetter under RCP8.5 while the opposite happens for the south part (Figure 75). As for other regions, a fundamental role is played by the influence of the Atlantic Ocean. Hydroclimatic variables projection affect substantially streamflow, which is generally reduced in the north, but with a magnitude which reflects the conclusions made above for precipitation (Figure 76). In the south, more water availability will be experienced. Water availability is higher in RCP2.6 than under RCP8.5, probably due to the horizon considered. Indeed, under RCP8.5, the increased water availability due to glacier melting will have already taken place before the years 2040-2060. On the other hand, under RCP2.6, glacier melting will occur at a slower rate and later in time resulting in more sustained high streamflow during this period.

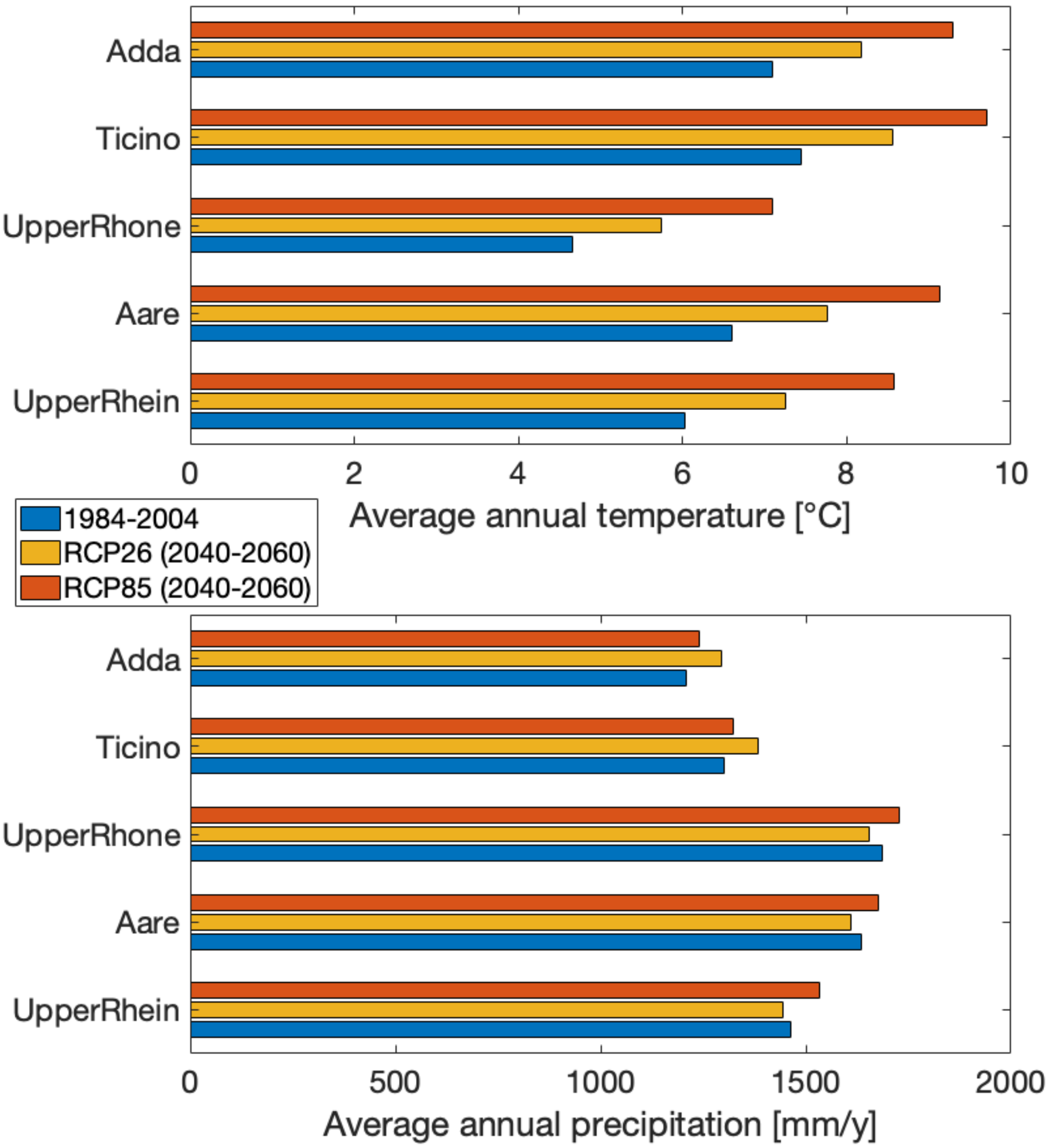


Figure 75: Average annual precipitation and temperature over the main river basins in the Alps. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow, RCP8.5 2040-2060 in red.

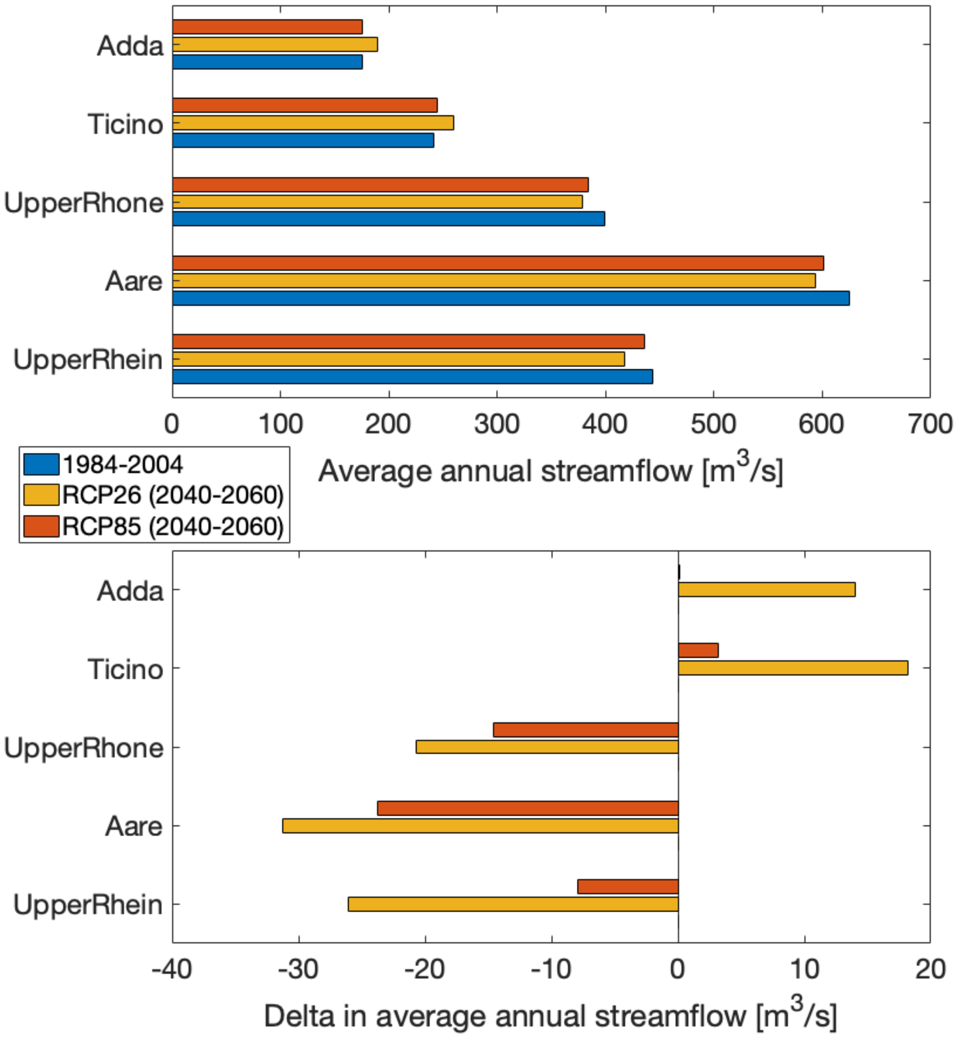


Figure 76: Average annual streamflow and its delta with respect to the historical conditions over the main river basins in the Alps. Historical conditions 1984-2004 in blue, RCP2.6 2040-2060 in yellow, RCP8.5 2040-2060 in red.

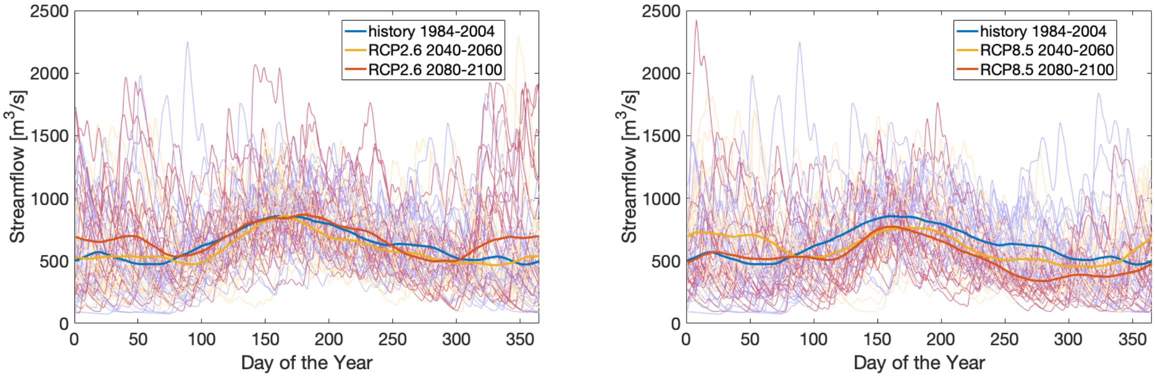


Figure 77: Klingnau hydropower plant streamflow projections under RCP2.6 (left panel) and RCP8.5 (right panel) scenarios. The color of the lines refers to different time intervals. The faded thin lines in the background show each single year streamflow trajectory for the period considered while the thicker ones represent the cyclostationary average over the period.

It is fundamental to bear in mind that the Alpine region is very complex, and analyses carried out at the level of the major river basin do not necessarily match with what can be observed at the power plant scale. As an example, streamflow projections for the Klingnau hydropower plant in Switzerland are reported in Figure 77. The streamflow in the near future is not far from the historical conditions but looks wetter at the end of the century (especially from November to March) under the RCP2.6 scenario. Under the RCP8.5 scenario, in the short period more abundance in the first two months and a reduced spring and summer streamflow are observed. Further in time, much drier conditions with very large reduction of summer streamflow, especially at the end of the summer occur.

Comparison between 2015 and 2040 energy system

The analysis between today and 2040 focusses on different parameters in the five countries Austria, France, Germany, Italy and Switzerland. The key parameters analyzed in this study are

– energy production in TWh
- electricity exchange between the countries
- hourly marginal price developments
- development of annual load curves
- typical operation of hydro power plants

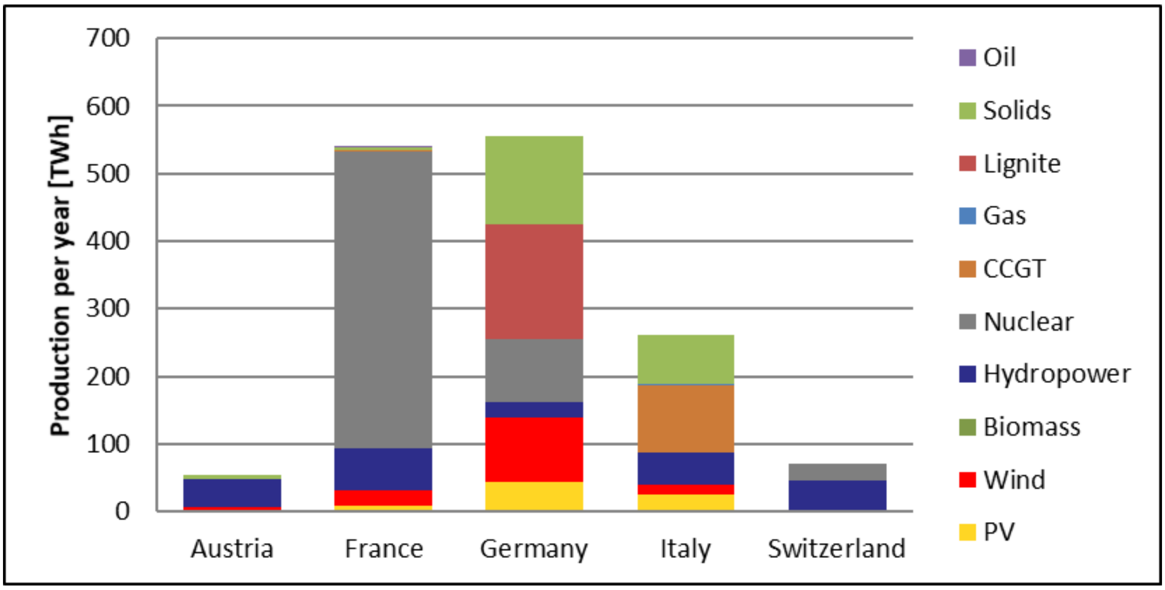


Figure 78 : Generated energy by power plant type in the reference scenario (2015)

The energy production in the 5 countries is based on different technologies (Figure 78). All countries are producing energy with hydropower to varying degree. France and Italy have the highest hydropower production with 63 TWh and 48 TWh respectively. The rest of the energy production in France is based mostly on Nuclear Power, Wind, PV and some other technologies which only have a minor share. In Italy the hydropower is combined with CCGT, solids, PV and wind power. The different composition of energy production in both countries underscore the versatility of hydropower which can be used for base load or peak power production based on the rest of the energy system. In Austria and Switzerland hydropower is the main producer of energy. Even with those two countries the rest of the energy production portfolio is quite different. Austria gets the rest of its electricity from solids and wind power. Switzerland on the other hand gets quite a bit of their energy from nuclear power. While Germany has the highest energy production, the production from hydropower is the lowest of all countries. This is due to the low potential for hydropower in Germany. Therefore, hydropower plays only a minor role in the German energy system. Due to long years of state subsidies Germany has the highest production of intermittent renewables (wind, PV) of all the five countries. The largest power producers today are still lignite and solids which produce over 50 % of the German electricity. The expansion of wind and PV capacities in the last two decades has led to a surplus of power plant capacities, which results in the small power production of peaker plants like gas and CCGT.

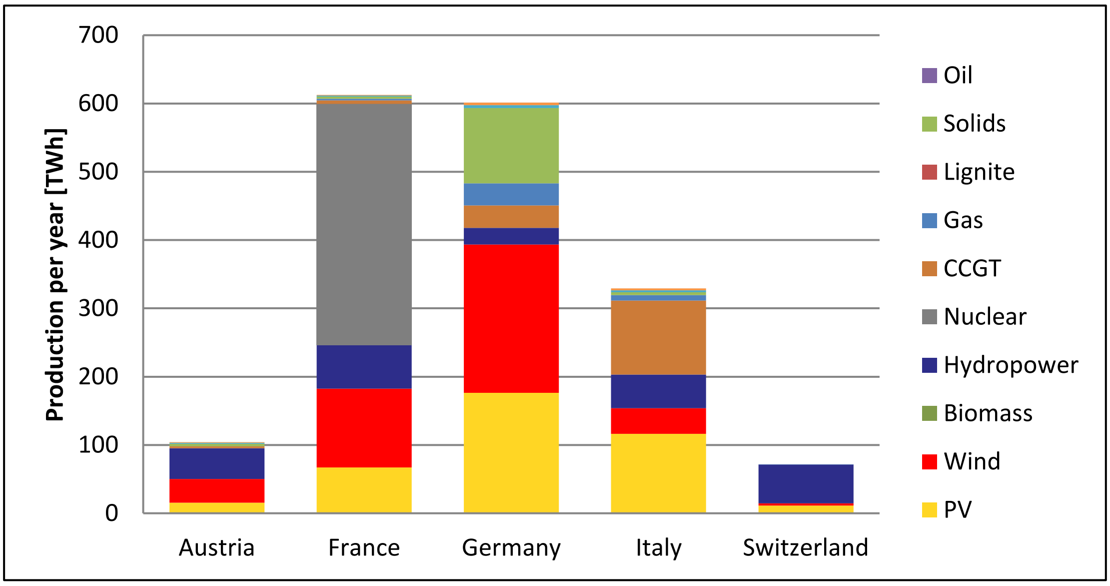


Figure 79 : Generated energy by power plant type in the standard scenario (2040)

When looking at the electricity production for all 5 countries in the 2040 standard scenario Figure 79 shows that the electricity production from wind and PV is much higher than in the reference scenario. This additional electricity is needed for the higher demand in all future scenarios as well to substitute the electricity that was produced by CO2 intensive power plants as lignite and solids. Austria produces more electricity than in 2015 due to the additional wind and PV capacities. In France some of the renewable electricity substitutes some of the nuclear energy. Germany produces about two thirds of their energy from wind and PV while the rest comes from a mix of Solids, Gas, CCGT and Hydropower plants. The surplus of overcapacities is reduced due to the lignite and nuclear phase out. Italy produces almost half of their energy from renewables. Almost all of the remaining electricity comes from hydropower and CCGT power plants, due to the solid phase out. Switzerland produces a bit more electricity from wind and PV. The power production from hydropower has also increased, which indicates that in the 2015 scenario not all of the available energy potential from hydropower was used due to the nuclear power plants.

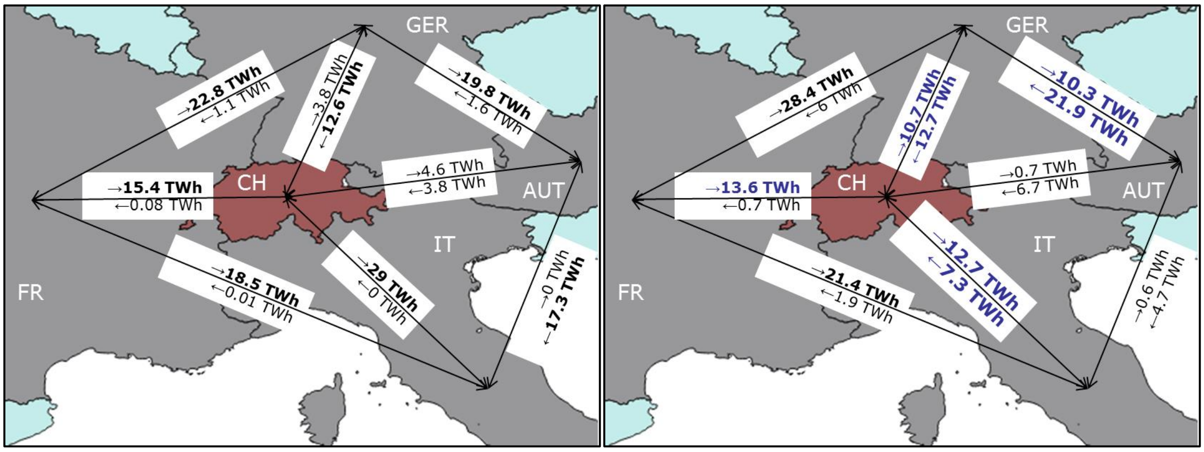


Figure 80: Grid transmission in the reference scenario (left) and the standard scenario (right)

By the different technology developments in the different countries, the electricity exchange in 2040 will change strongly. The maps above show the electricity that is exported and imported in the modelled year. The left map shows the reference scenario in 2015 and the right map shows the standard scenario in 2040. In both scenarios France is the greatest net exporter due to their large fleet of nuclear power plants and hydropower with their low marginal cost. In the standard scenario in 2040 France is also the second largest producer of renewable electricity. Due to the additional renewable generation Austria imports decrease as well and exports increase in the standard scenario. Due to the increasing electricity demand Germany import more electricity in the standard scenario than in reference scenario. Italy which imports a lot of electricity in the reference scenario, is still importing more energy than exporting in the standard scenario, but the im-/export balance has about halved compared to the reference scenario. Due to the increase in energy demand and only slight increase in renewable energy power plants, Switzerland is importing more energy in the standard scenario than in the reference scenario. Table 25 shows the total import and export of each country in the reference and standard scenario.

Country	Import Reference Scenario [TWh]	Export Reference Scenario [TWh]	Import Standard Scenario [TWh]	Export Standard Scenario [TWh]
Austria	24.4	22.7	11.6	33.3
France	1.19	56.7	8.6	63.4
Germany	28.2	33.5	61	29
Italy	64.8	0.01	38.8	9.8
Switzerland	31.8	37.48	40.3	24.8

Table 25 : Sum of im- and export in the reference and standard scenario

The goal of the optimization is to minimize the total costs of the unit commitment problem and meet the electricity demand for each hour and country. The costs are therefore fundamental to understand the operation of power plants, storages and transmissions. The marginal cost for the energy demand shows the marginal cost for the most expensive power plant that is running for every hour. The marginal cost show how much the production of an extra MWh would increase the total costs. The costs depend on the demand and the power plants available for every hour and country. Figure 81 & Figure 82 show the marginal costs for all five countries in January for the reference and standard scenario respectively. With the exception of Italy, the marginal cost of the other countries is in between 20 to 50 € per MWh in the reference scenario. The marginal costs in the standard scenario are a lot more volatile and range within 5 to 68 € per MWh.

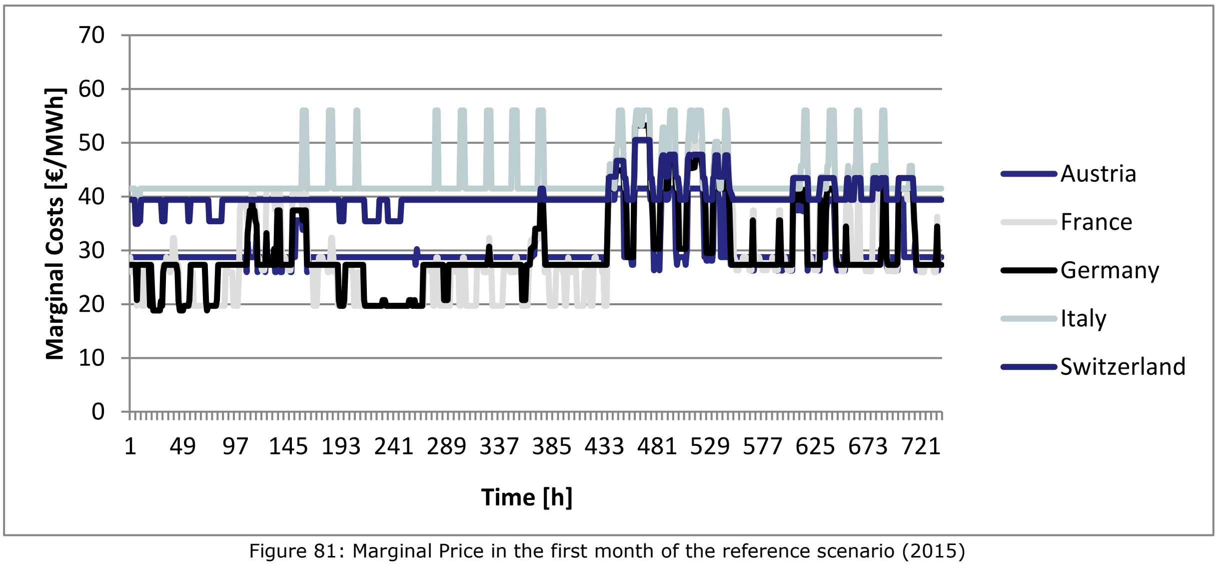


Figure 81: Marginal Price in the first month of the reference scenario (2015)

The low prices are due to a higher penetration of renewable power sources with low marginal costs. The higher costs are due to increased marginal costs for conventional power plants due to increased fuel prices and a higher CO2 Price. Another reason for the lower prices in the reference scenario are the overcapacities of low marginal cost power plants like nuclear, lignite and solids. The higher price spread in 2040 is an advantage for storages and reservoir hydro power plants and results in a higher usage for such technologies compared to 2015.

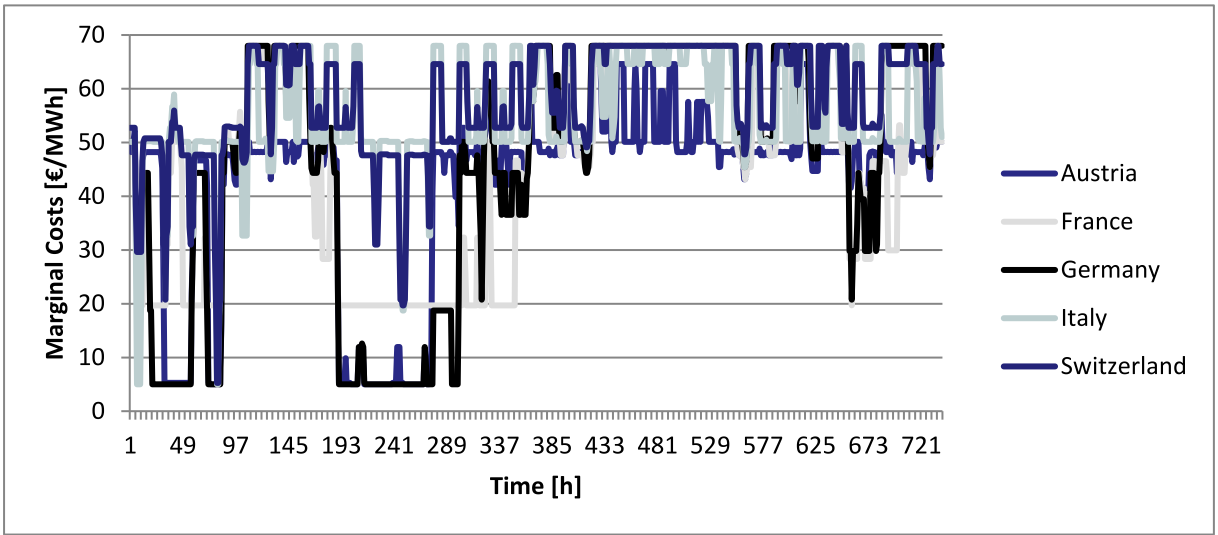


Figure 82: Marginal Price in the first month of the standard scenario (2040)

Focus on the hydro system of Switzerland

This chapter is focused on the changes in the operation of the power sector in Switzerland due to the changes in the power plant portfolios in the reference and standard scenario. Furthermore, there is a comparison of two weeks of power production in the standard scenario to show the status of the energy system in the right time order. The changes of operation for a whole year can be best seen in a sorted annual load curve. Figure 83 & Figure 84 show the sorted annual load curve for Switzerland in the reference and standard scenario, for run over river, reservoir generators and pumps, gas and nuclear power plants. The sum of the power production of all turbines in reservoir hydro power plants and pump storages is aggregated under generator hydropower. Pump hydropower is the aggregated power draw from the pumps in the pump storages. Other renewables are not included.

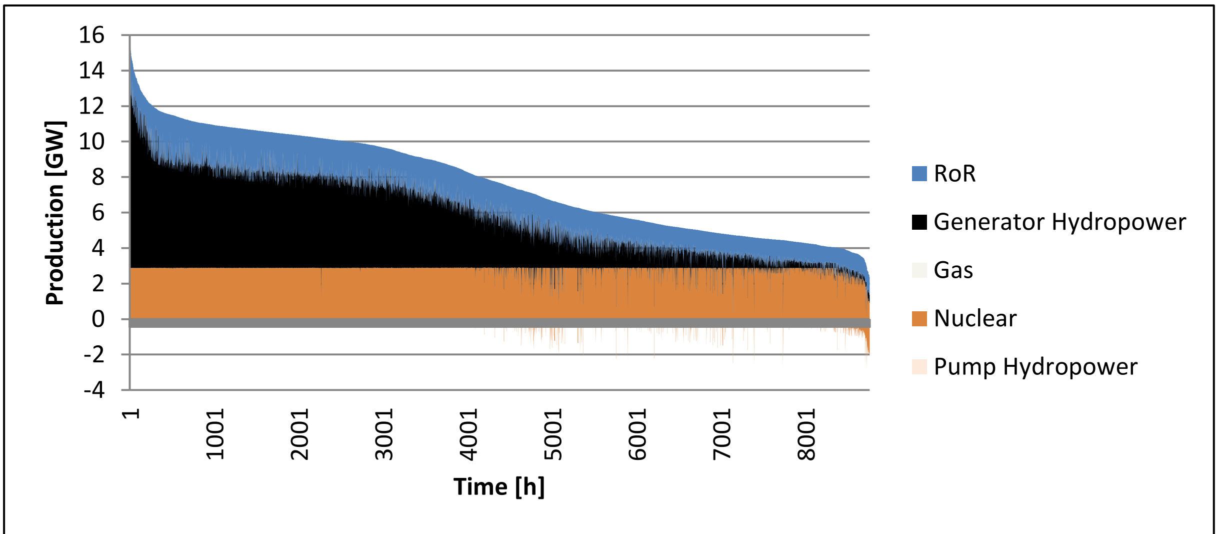


Figure 83: Annual load curve for Switzerland without renewables for the reference scenario

In the reference scenario nuclear is used throughout the year as baseload power plant. The pumps from the pump storages are rarely used to store energy. The pumping is visible through the values where the bars start at negative numbers. The power output of the run over river power plants is mostly stable, but has some variations that are depended on the intermittent streamflow. Reservoir hydropower plants are used to balance the electricity demand and production. The full capacity of 16.34 GW of the hydropower plants is not used at any hour of the year. The highest power production is about 16 GW from which 2.9 GW is supplied by nuclear power. The utilisation of the turbines in pump storages and reservoir hydropower plants varies greatly throughout the year.

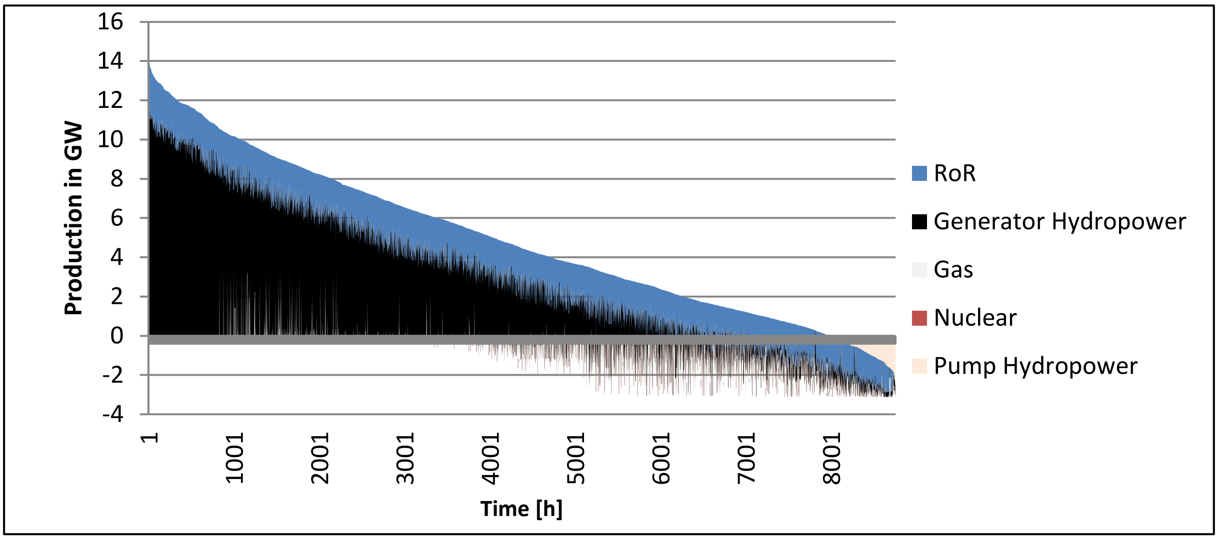


Figure 84: Annual load curve for Switzerland without renewables for the standard scenario

There are only 73 hours in the year where the power output of turbines in pump storages and reservoir is over 9 GW and 693 hours in the year with a power output over 6 GW and 6500 hours where the produced power is over 1 GW. The same numbers for the standard scenario are 706 hours, 2164 hours and 6633 respectively. These numbers show that the number of hours in which a high or medium power output is needed increases in the standard scenario, while the number of hours where the power production is very low only decreases slightly. In the hours with lower production the energy comes from nuclear in the reference scenario and from renewables and mostly imports from other countries in the standard scenario. In the hours of high power production from hydropower plants, the electricity is either used to meet a high residual load in Switzerland or exported to other countries to meet a high residual load in those countries. This is also visible when the total of the load curves is compared. In the reference scenario there are 2584 hours where the total power production is higher than 10 GW. In the standard scenario this power production is only reached in 1084 hours. Since the demand is also increasing in the second scenario the dependency on imports and renewables is notable.

To get the full picture of the energy system it is also necessary to look at the production of electricity at normal timescale. Therefore the next two figures, Figure 85 & Figure 86, show two weeks in the standard scenario in 2040. These weeks show the different statuses of the energy system in Switzerland. They also show different usages of the pump storages and hydropower reservoirs. The figures show the production of all power plant types in the country as well as demand, import and export. The area of the graph that is under zero is the power that is used in the pumps of the pumps storage. The area that is above the red demand line is the electricity that is exported in other countries. The exports are transparent to allow a full picture of the power production. The first graph shows the second week of the year, in which Switzerland imports a lot of its electricity from other countries. Most of the time, the pumps are active during the middle of the day while PV is generating most of their electricity. The pumps are also running, when there is a lot of imported energy from other countries. The turbines of the hydropower reservoirs and storages are not running most of the time, except for the late evening when the power output from PV is decreasing. The second week shows the case when Switzerland exports a lot of electricity to other countries.

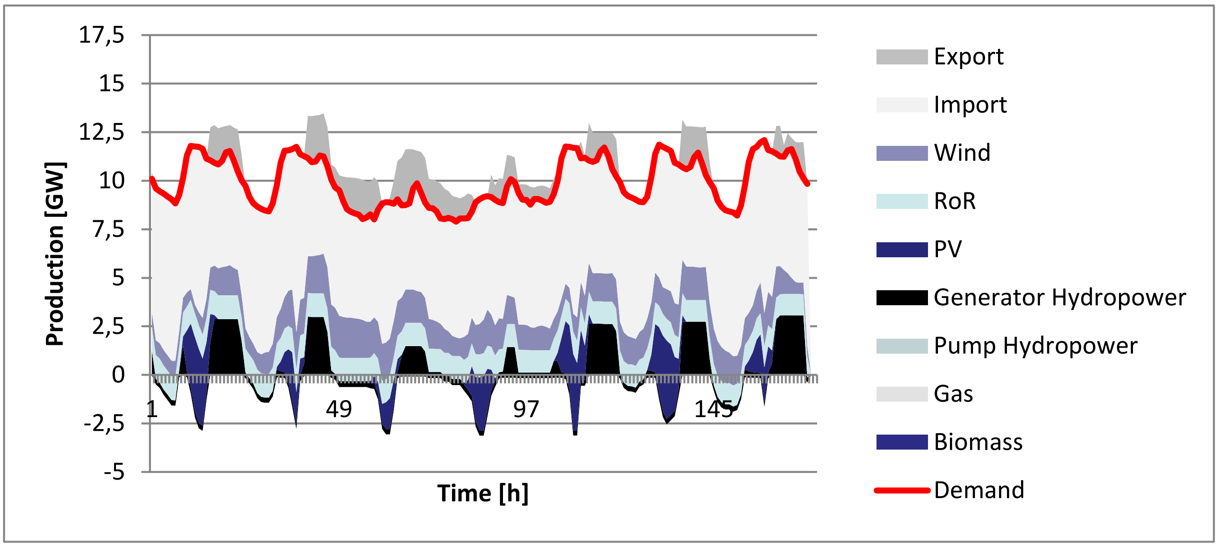


Figure 85: Production, transmission and demand for the second week of the standard scenario

The pumps are still active during every day, since the amount of exported energy is rather low. During the day a lot of electricity is imported from a neighbouring country and directly exported to another country. On most days there is a lot of electricity produced from the afternoon through the night that is exported to other countries. While the run over river production is quite stable, the production from reservoir hydropower is changing a lot during the day. During the middle of the day the power output is only at 2-3 GW. The energy that is saved or stored during that time is used in the afternoon. Due to the high energy demand and export the power output of the reservoir power plants reaches the maximum power output of 12 GW. The energy demand is so high that the energy that is saved in other weeks such as Figure 85 is used as well. Therefore, this week shows the simultaneous usage of hydropower reservoirs as short and long time storage.

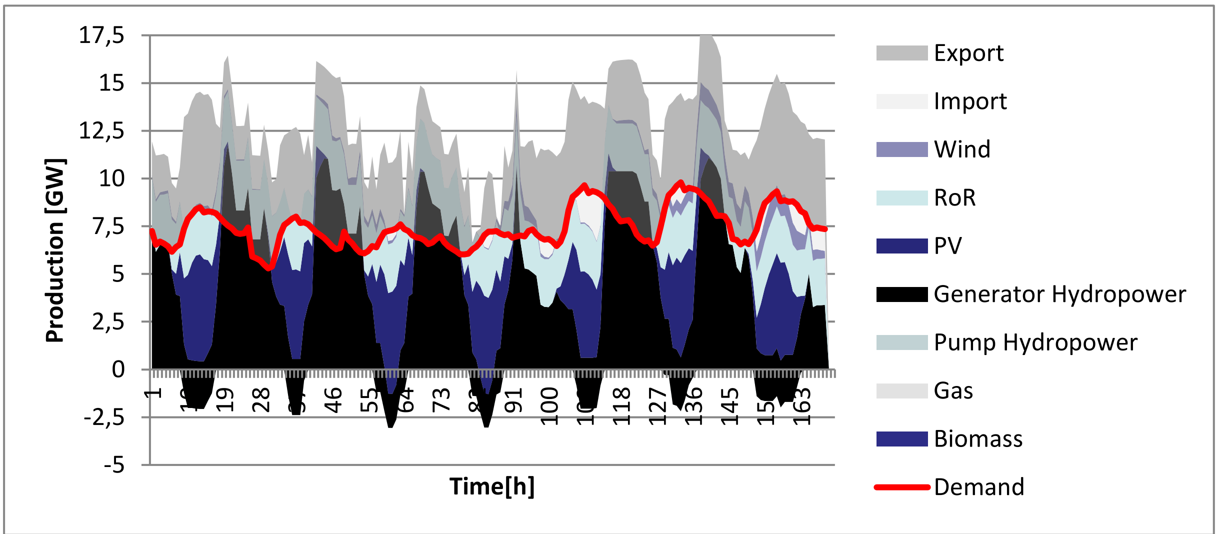


Figure 86: Production, transmission and demand for the 26th week of the standard scenario

Focus on the Pump Storage Veytaux Switzerland

The pump storage Veytaux in Switzerland was selected to show some of the effect of different scenarios on a single power plant. The power plant has a turbine power of 420 MW in the standard scenarios and 840 MW in the HighFlex scenarios. The power of the pump is 437.4 MW in the standard scenarios and 1312.2 MW in the HighFlex scenarios.

Figure 87 shows the full load hours over all scenarios for the turbine and the pump. In the reference scenario the full load hours are rather low with a total of 917 full load hours for the turbine and 426 for the pump. This is a lot lower than in all other scenarios. If we compare the standard and the standard 8.5 scenario it shows that the different climate scenario doesn't have a big influence on the operation of the pump storage. Even the high-flex scenario which is identical to the standard scenario with the exception of the capacity of the turbine and pumps shows a bigger difference in the full load hours. The standard scenario is also the scenario with the highest full load hours of the pumps. The HighFlex scenarios have the highest number of full load hours, but the lowest number of pump full load hours. This can be explained by the bigger pumps in those scenarios.

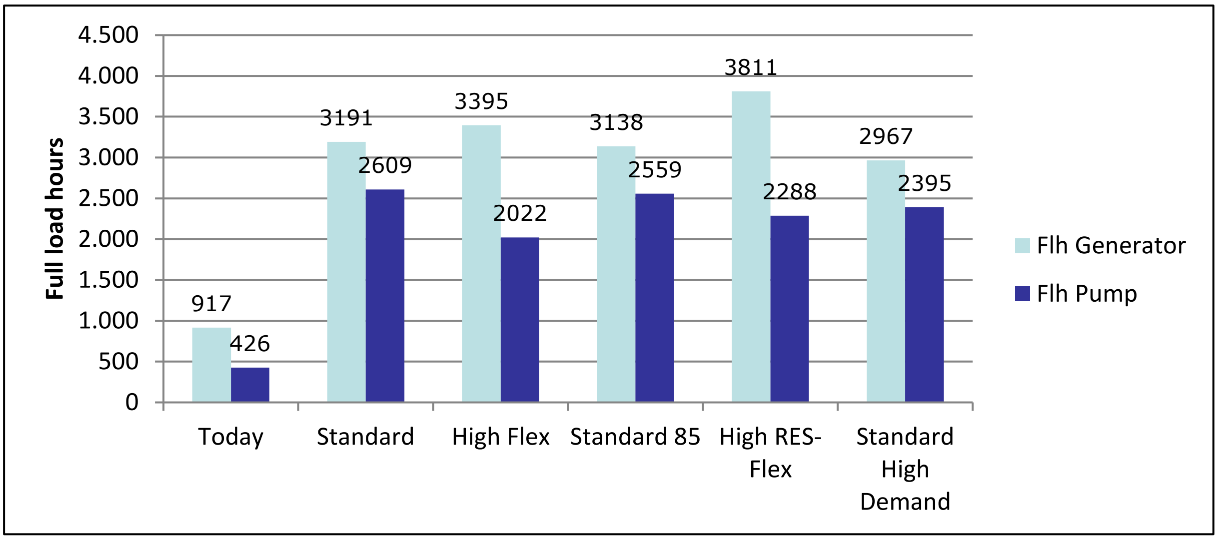


Figure 87: Full load hours for the turbine and pump of the Veytaux pump storage in all scenarios

Figure 88 shows the average marginal clearing price for the turbine and pump in all scenarios. It shows that the difference in the marginal clearing price in the today's scenario is about 4 €/MWh. Even if the standard scenario has the lowest marginal prices for the pump on average, the bigger price difference in the other scenarios leads to a higher usage of the pumps. The lower prices in today's scenario are due to lower fuel costs and some overcapacity in today's conventional power plants.

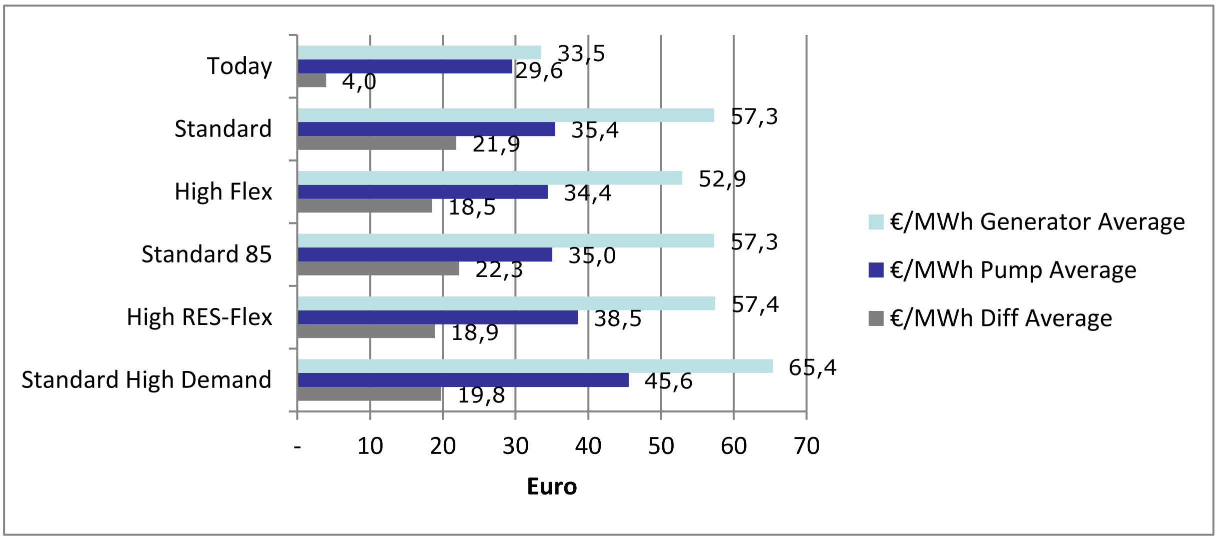


Figure 88: Average Marginal Price for the turbine, pump and the average price difference in all scenarios

Hydropower flexibility maps

As seen in 5.3.1, glacier and snow melting are of fundamental importance for the alpine region. Water availability is expected to increase due to increased temperature resulting in glacier melting. Nonetheless, this will be only a temporary effect of climate change: once this water is gone, it cannot be used anymore. The timing and the magnitude of such phenomena will play a fundamental role in alpine reservoir operations and their contribution to flexible electricity generation.

Indeed, flexibility maps reflect the relevance of the glacier melting and of its effect for hydropower plants in the Alpine region (Figure 89). Under RCP2.6 there is a quite clear separation with less flexibility in the south-east and more in the north and north-west. Under the RCP8.5, higher temperatures and increased streamflow due to glacier melting reduce controllability of streamflow in many power plants making them less capable of providing the additional flexibility required by the future energy system.

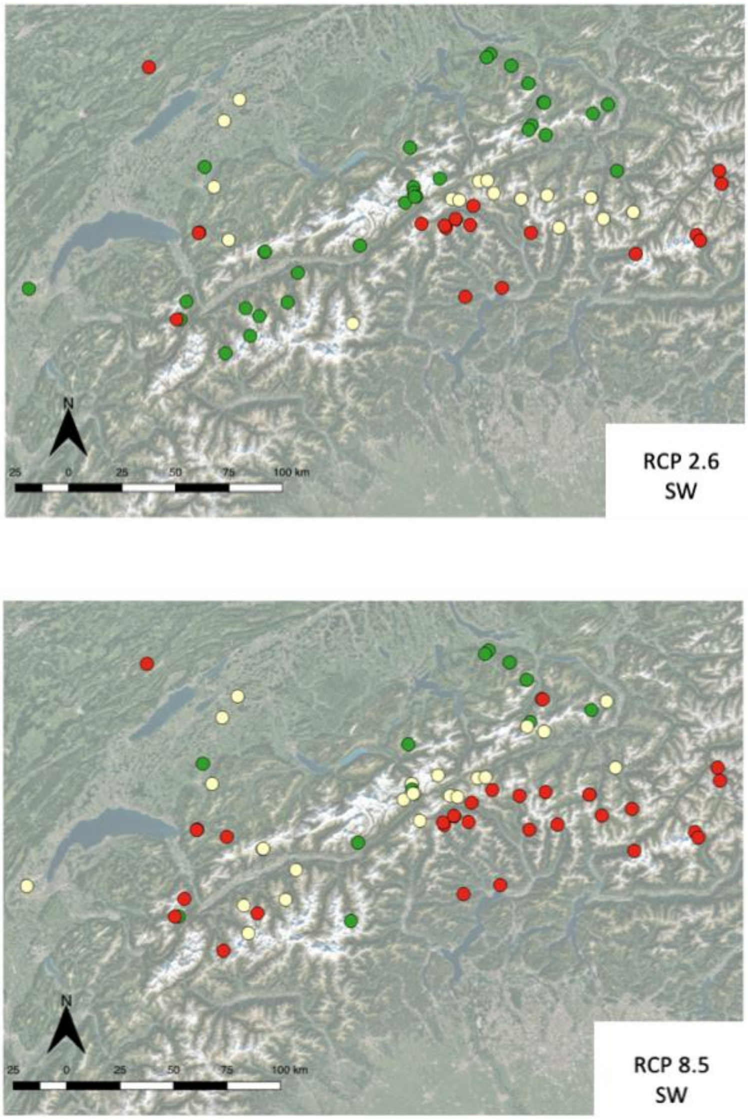


Figure 89: Flexibility maps for the Alpine region under RCP2.6 (top panel) and RCP8.5 (bottom panel). Green color represents more flexibility, red color represents less flexibility. Yellow dots show no significant change.

5.4 Adda river basin

Observations made above about the temperature projections in the Alpine region hold for the Adda river basin too: a larger impact on temperature is observed under RCP8.5 (Figure 90), with the impact generally emphasized in winter months. For what concerns the precipitation, under the RCP2.6 scenario an anticipation and an increase of spring and summer rainfall is observed, while it reduces in summer. Considering the RCP8.5, the increase and anticipation of rainfall in winter and spring is evident while the reduction in summer is more pronounced. Indeed, precipitation assumes a bimodal distribution at the end of the century: one peak in spring and a smaller one in autumn.

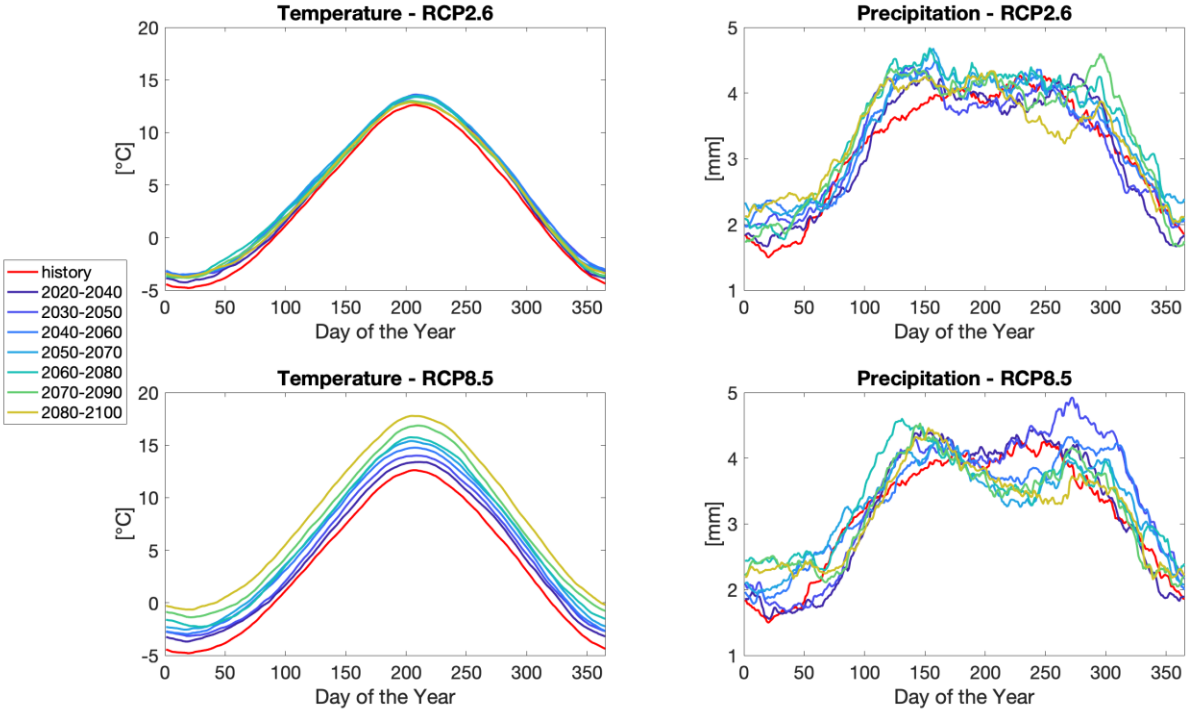


Figure 90: Adda river basin average temperature and precipitation projection under RCP2.6 (top panels) and RCP8.5 (bottom panels) scenarios. The color of the lines shows the time period considered in order to describe the evolution in time of these variables. The lines reported are the cyclostationary average over the time period considered.

In Figure 75, average annual precipitation and temperature for the whole Adda basin are reported. In the following, the focus is more on the upper Adda basin, where the most important hydropower plants are located.

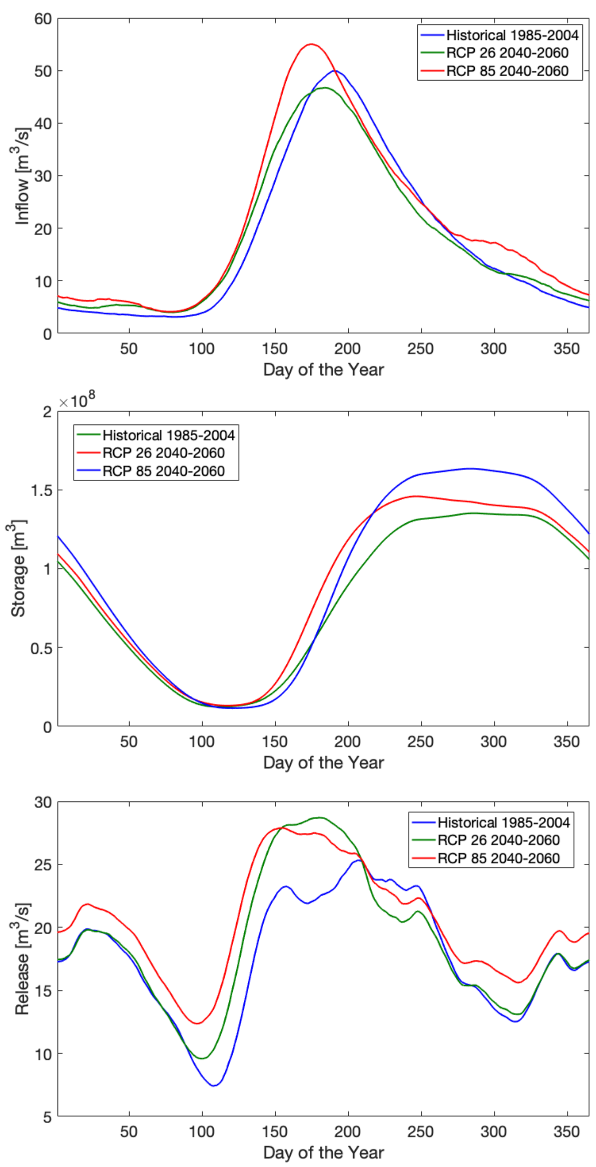


Figure 91 : Inflow (top panel), storage (middle panel) and release (bottom panel) cyclostationary trajectories under historical conditions (blue), RCP2.6 (green) and RCP8.5 (red) scenarios.

The above observations have a direct effect on the management of the Cancano reservoir, one of the most important reservoirs in upper Adda river basin, for which cyclostationary trajectories are reported for inflow, storage and release (Figure 91). The peak of the inflow is anticipated in both RCP2.6 and RCP8.5. Under RCP8.5 scenario, more streamflow in average is observed. This allows to fill up the reservoir before and to release more water throughout the year, resulting in an increased hydropower production over the period, especially under RCP8.5. This is due mostly due to melting of the glaciers above this dam. This water is made available for use thanks to the higher temperature. Anyway, it is important to remember that this is a short-term benefit of the climate change. On the long run, the glacier will melt, and production will be reduced at the end of the century.

Soft Integration

Figure 91 illustrates the trajectories of inflow, storage and release under different climate scenarios obtained simulating an optimal reservoir operation designed via Stochastic Dynamic Programming[44][45] with the objective of maximizing the hydropower revenue using the electricity prices observed in the period 2009-2015. The effect of a change in electricity prices was also assessed using a soft integration methodology, where the reservoir operation is re-optimized with the prices coming from the analysis of the

ENTIGRIS energy system model for the alpine region (shown in Figure 92). This feedback loop is important as it allows projecting the water-energy nexus interactions in the future.

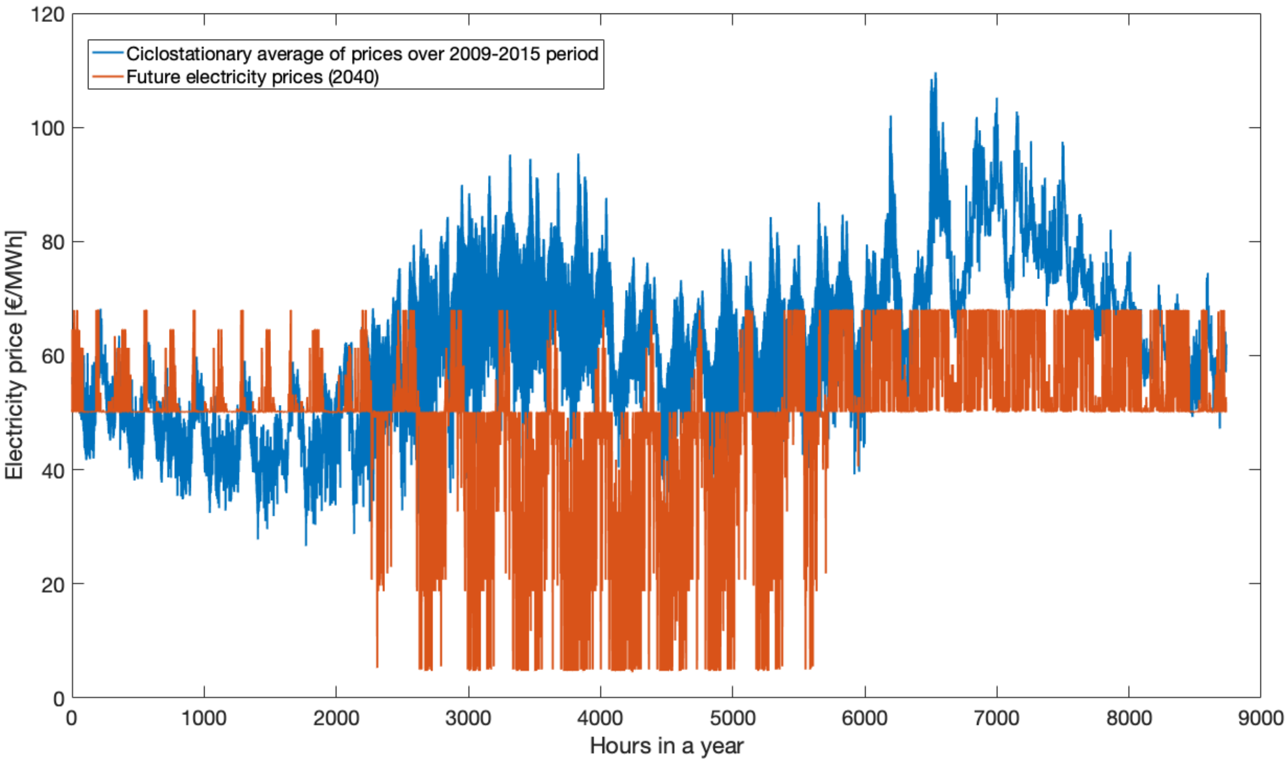


Figure 92: Prices trajectories over the year: observed 2009-2015 (blue) and future electricity prices obtained from ENTIGRIS (in orange).

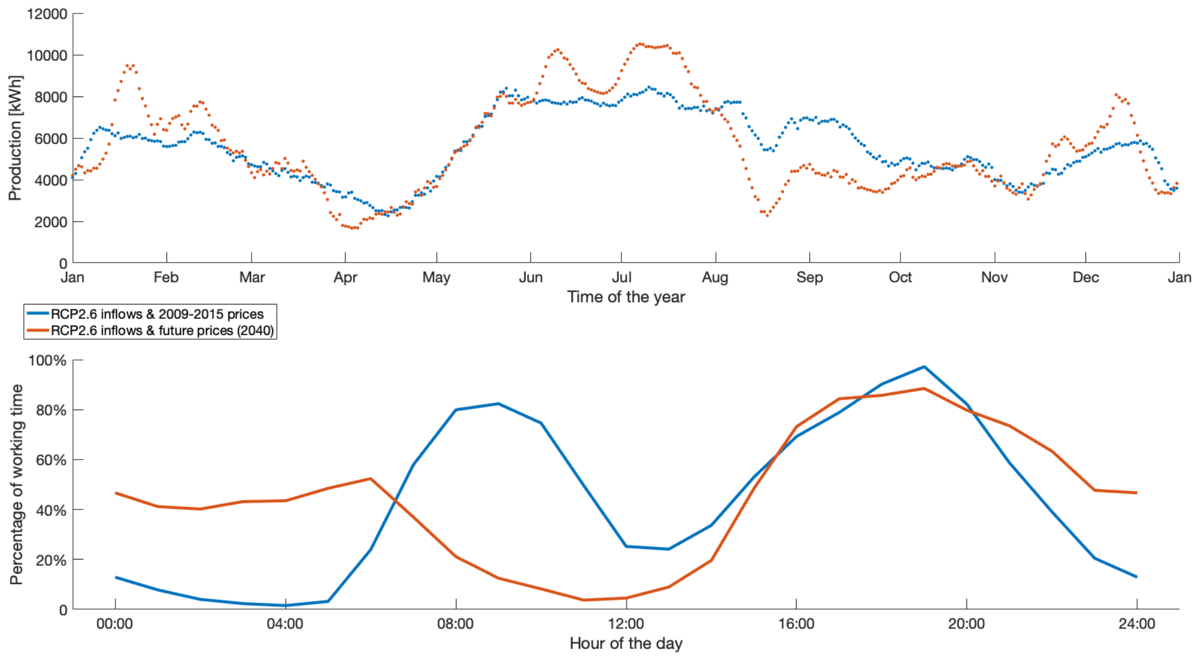


Figure 93: Top panel: cyclostationary daily production from Cancano reservoir optimized with respect to observed (blue) and future (orange) prices trajectories. Bottom panel: hourly working time percentage over 20-year simulation period with obeserved (blue) and future (orange).

After the re-optimization of the reservoir operation using the projected price trajectory, hydropower revenues are substantially affected but not the total generation over the year, which doesn't change (Table 26). On the other hand, the generation is distributed differently in time: with the future energy prices more production is expected to take place during winter and less in August and September. At the same time, the daily pattern will change substantially. The increased penetration of renewable energy sources will reduce the price during daytime and consequently hydropower generation will wait for prices to rise again (at night) to increase the profit (Figure 93).

Table 26: Cancano reservoir operation optimization: mean annual revenue and mean annual production over 20-year period. Inflows and prices are used for both optimization and simulation.

Inflows	Prices	Mean Annual Revenue [M€]	Mean Annual Production [GWh]
1984-2004	2009-2015	141.05	1.86
RCP2.6 (2040-2060)	2009-2015	148.80	1.99
RCP8.5 (2040-2060)	2009-2015	159.80	2.16
RCP2.6 (2040-2060)	2040 (ENTIGRIS)	115.12	1.99
RCP8.5 (2040-2060)	2040 (ENTIGRIS)	123.83	2.16

6 US-EU water and power modeling workshop

This project relates the EU efforts within a US-EU initiative on energy-water nexus. In the course of this project two sets of online webinars were undertaken to debate and compare the modelling methodologies.

In Washington on December 6th and 7th 2018, a final meeting took place which focused on the themes around the energy-water nexus.

On the first day, the institutions involved in the joint US-EU initiative presented their work and their results. Some major differences emerged about the spatial and temporal scales analyzed: the range from urban to regional scale was covered with decreasing temporal resolutions. As a consequence of this difference, also the energy and water fluxes considered varied significantly from one study to the other.

The heterogeneity of the different projects displayed the many aspects involved in water-energy systems modelling and the various issues arising due to the specific modelling objectives of each study.

After the presentations, different themes were debated. It emerged that different scales lead to different systems integration problems. In addition to that, many difficulties arose when defining the flexibility of the water system and metrics to quantify it. Overall, an enlargement of the system analyzed was proposed as a solution in order to describe other water uses which are usually neglected.

7 Conclusions

In this study, hydrological and power system models were adapted in order to study the impact of climate change on water availability for power systems and its functioning, as well as flexibility options.

For this purpose, a methodology was developed which links future hydro-climatic projections to future power system developments. The vulnerability of the power system to changes in the hydrological system due to climate change was quantified. Currently the water and power systems are not managed together although there are strong linkages between the two systems; neglecting these linkages can lead to lack of exploitation of synergies as well as underestimation of the risks.

The study has analysed three macro-regions in Europe: the Iberian Peninsula, the Danube river basin and the Alpine region with a focus on Switzerland. A further micro-region study of the Adda river basin performed a soft-linkage between the two system models (hydrological and power system) to analyse feedback loops and mimic real time performance.

On the hydrological side, an automatic modelling chain was developed for this project which undertakes basin delineation, hydroclimatic variables processing, hydrological models' calibration, validation and simulation. A very large amount of data was required to be processed to simplify and extract the variables required by the power systems. The hydro models used in this analysis were the (adapted) HBV model for the macro-regions and the Topkapi-ETH model for the micro-region.

On the power side, two different power models were used the PRIMES-IEM and the ENTIGRIS model. The models were adapted in order to include the water indicators as constraints for the power system. The models analysed different climate scenarios with resulting different water availabilities on the power system in 2040 in a context of a decarbonisation scenario. The analysis was limited to the functioning of the power system maintaining constant the power plant capacity by type of power plant and not including the imports/exports with neighbouring regions, therefore testing the resilience of the power system under changed climatic conditions.

Iberian Peninsula

The Iberian Peninsula is a very arid region of Europe and very likely to be affected by future climate change. Two major changes are expected in the power plant park until 2040 compared to today: the decarbonisation of power generation driven to a large extent by an increase in the renewable energy capacity and a continuation of the trend of equipping the new power plants with wet-recirculating cooling systems. Both trends contribute to making the system more resilient to changes in water availability by reducing the water consumption. The analysis shows that the electricity system is reliable under limited climate change impacts (2°C scenario), but that it lacks mechanisms to face extreme climate conditions of low precipitation and high water temperature.

Portugal is heavily dependent on electricity imports from Spain, which are highly increased as power generation from hydroelectric power plants is reduced due to arid climate conditions. On the other hand, Spain covers the loss of hydro generation with increased generation by fossil fuelled power plants. In extreme climate conditions, several days a year load cuts are observed, because of the significantly reduced hydroelectric availability in Spain and Portugal and the shut-down of nuclear plants.[18]

Under dry conditions, the higher use of fossil power plants leads to increasing CO_2 emissions: these are found to almost quadruplicate in extreme climate conditions. Further in the drier conditions, the changed operation of the power system actually leads to additional water consumption, due to higher use of fossil power plants, further exacerbating the stress on water supplies.

The dry conditions obviously also have a huge impact on the average System Marginal Price, driving it to almost 200 €/MWh in the RCP8.5Extremedry scenario and leading to a dramatic increase of the total system cost for power generation.

Only the effects of climate change on water availability have been analysed in this report; if water scarcity is combined also e.g. with lower wind availability, the stability of the system would be highly questionable.

With regards to water availability the system of the Iberian Peninsula becomes more resilient to the effects of climate change reducing its water dependence with increasing penetration of RES as expected in a decarbonisation context. While increasing its reliability to extreme conditions, the system nonetheless remains vulnerable due to its dependence on hydro availability.

Danube River Basin

The nature of the Danube River Basin watershed makes the local electricity system quite resilient to climate change due to its size. In the time period until the mid of the century the snow dynamic of the Danube region leads to higher streamflow due to more snow melting in drier (and most likely warmer) years; the impact on hydroelectric power generation is therefore expected to be limited. In extreme dry cases (in this study under scenario RCP8.5 Extreme-dry) however, the reliability of the Danube's River Basin electricity system can be compromised and load cuts are observed.

The limited effect on the hydroelectric power generation over the scenarios is reflected into very moderate increases of the average System Marginal Price, compared to a no climate change scenario; however, under extreme dry conditions the effect will be substantial with a 130 €/MWh increase compared to the no climate change reference case.

Water withdrawals decrease in the drier scenarios –relative to the no climate change case- as the hydro-generation is substituted by fossil power plants using wet-recirculating cooling systems with low withdrawal intensity. Water consumption however increases in drier scenarios because the power plants consume water in their cooling system, further stressing the water systems, the water consumption is however considerably lower than today due to the changes in the power generation structure.

With the higher use of thermal power plants –under dry conditions- the carbon intensity increases, even doubling in the extremely dry scenario quantified here. All of the above contribute to an increasing total system cost under intense water scarcity conditions.

The power generation system of the Danube river basin will become more resilient to climate change when pursuing decarbonisation. However, the system continues to rely significantly on water availability: in the longer run (end of the century) when snow melt patterns may differ, the system can suffer significantly.

[18] It is reminded that by assumption imports (and exports) are assumed to be fixed with neighbouring regions in the scenarios analysed, as well as the configuration of the power plant park.

Alpine region

The study of the Alpine region shows that flexible hydropower power plants especially reservoir hydropower and pump storage play an important role for the future energy system with a high share of renewable energy. The pump storages can store surplus energy in time of a high wind and PV infeed in Switzerland or neighbouring countries. In times of peak net load the hydropower reservoir power plants and pump storages have quick response times to produce the required power to meet the electricity demand. Currently pumped storage plants are rarely operated economically, however this could change substantially in the future. All future scenarios have a higher spread of marginal costs, due to a changing generation structure. The spread increases due to the zero marginal costs of wind and PV and the high marginal prices of fossil fuel power plants. The number of hours with zero marginal costs will increase in the future due the to higher penetration of renewable power plants. The marginal costs of fossil fuel power plants are likely to increase on the other hand, due to fuel and ETS allowance prices. Both of these developments benefit the use cases of pumped storage plants or other energy storage solutions. Due to the projected changes, the full load hours for pump storages are increasing in all future scenarios. With the data collection and model expansion –started within this project- it is possible to analyse the operation of single power plants.

This analysis was undertaken for an exemplary pump storage plant –Veytaux- where the full load hours for the turbine are increasing sharply in all future scenarios. The twofold increase in turbine power and the threefold increase in pumping power results in higher turbine full load hours and lower pump full load hours. This plant also shows that the difference in technology portfolio and volume of installed RES capacity has a higher influence on the results compared to different climate scenarios. Due to the fact that there is not much difference between the climate 2.6 and 8.5 scenario in total streamflow per year in the Swiss Alps, there is only a small influence on the costs and full load hours of a single pump storage power plant.

Adda river basin

As for the high-resolution case, the soft integration methodology shed new light on the interactions among the water and energy systems. These, together with climate change impacts, will substantially affect the way hydropower companies will behave in the future. Interactions were accounted for. This was done by iterating model runs of both energy and water systems allowing for information exchange between them. This procedure showed indeed the capability of describing simple adaptation mechanism of the systems with respect to each other.
In the case study, over the period 2040-2060, streamflow is projected to increase as an effect of glacier melting due to warmer climatic conditions. Nevertheless, as a result of the increased renewable energy sources penetration, future energy prices will shrink reducing the annual revenue with respect to historical conditions. At the same time, solar energy will further reduce daytime prices producing a shift in hydroelectricity generation towards night time, a pattern already observed with the introduction of renewable energy sources and market liberalization.
Due to the nature of our case study, the hydropower sector was more responsive to changes in prices, which were computed at the energy system scale. The energy system's reduced reactivity to alteration of hydropower generation in the Adda river basin was probably due to the larger scale used in the energy model.

Suggestions for further research

The current research focused on combining hydrological detailed data by power plant location to power models in order to verify the effect of change water availability in climate scenarios on the functioning of the future energy system. The study has found that, in pursuing decarbonisation, the energy systems analysed (particularly the Iberian Peninsula and the Danube River basin) become less reliant on water and therefore become more resilient to extreme drought circumstances. The analysis should be expanded to the entire European Union to verify whether all systems become more resilient and whether some regions would be particularly affected.

Further analysis should look into combining the water constraints into the long term planning strategy, in order to combine mitigation with adaptation strategies. Although the EU is committed to decarbonise its energy system, the probability of not remaining within a 2°C or even 1.5°C scenario is decreasing every day. It is therefore important that long term and long lasting investments –such as power plants- are planned both for mitigation purposes, as well as in view of adapting to a climate characterised by large scale changes of the climate and extreme weather events, which are expected to become relevant particularly in the second half of the century. Given the long life time of investments in power generation both elements should be taken into consideration.

A combined analysis of stress factors for future decarbonised power systems including water availability and wind availability may be interesting in order to obtain a tool which can fully cover strategic planning in the case of drastic climate change.

A further element which was not possible to analyse due to lack of data within this project is the possible flexibility deriving from the water system itself to be used by the electricity system: e.g. demand response measures within the water supply system. The use of electricity by the water system in the regions studied has been estimated at below 2% and includes desalination plants, water treatment facilities, water pumping within the water infrastructure and water pumping for agricultural purposes. In the EU such facilities are relatively small scale and require a micro-level analysis; the benefits are expected to be small and might result in limited additional flexibility to the system particularly at the distribution level. In the US such analysis has been performed e.g. by Laboratory for Intelligent Integrated Networks of Engineering Systems (LINES) of Thayer School of Engineering at Dartmouth: in this analysis a suit of models is used, in order to simulate simultaneously the operation of power and water system and analyse their interdependency by examining a variety of scenarios. Such information is very relevant for short term (daily/hourly) dispatch planning of TSO and DSO, but less for longer term strategic planning. The gains –in terms of flexibility- to be obtained from this additional effort are negligible for the system at a country level, although water supply companies may be interested to ensure energy and cost savings (use of water in low peak therefore low cost times).

Finally, large improvements can be done in hydropower modelling in energy models. A realistic description of reservoir management would highly improve the ability to describe future hydropower generation. As seen in the high-resolution case (Adda river basin), reservoir management will probably change in the future due to changes in inflow and electricity prices. Considering a stationary behaviour represents a strong hypothesis which needs to be replaced, but the modelling challenge is to describe these future changes at a large scale, which may require to properly cluster power plants in aggregated reservoirs with similar behaviour. Future changes in other water uses represent another modelling challenge and a limitation of this work. In this report, the energy system used net available water after other water uses (agricultural, drinking), under the hypothesis of these being stationary in the future. By using advanced modelling techniques and projections, different scenarios in water demand for the other sectors can be provided and used to make the analysis more informed and robust.

SUPPLEMENTARY MATERIAL

S.1. Watershed Delineation

A watershed, also known as basin or catchment, is the area from which rainfall flows into a river, lake, or reservoir and it is physically delineated by the upstream area from a specified outlet point. Watersheds can be delineated manually using paper maps or digitally in a GIS environment. The delineation process in this project was performed using ESRI's ArcGIS Desktop 10.5.1 software. The required data include a digital elevation model (DEM) and a stream network file for the area of interest. The spatial data used in the project and their sources are presented in Table 27.

Table 27: Spatial dataset information

	Dataset	Type	Institution	Temporal update	Source
Hydrological features	WISE[19] WFD[20] reference spatial data sets	Shapefile	European Environment Agency (EEA)	Jul 2017	https://www.eea.europa.eu/
DEM	European Digital Elevation Model (EU-DEM), version 1.1	Raster (25 m^2 resolution)	European Environment Agency (EEA), EU Copernicus programme.	Apr 2016	https://land.copernicus.eu/

The main steps performed in this project to delineate a watershed are described hereafter.

Step 1- Create a depression-less DEM

The *Fill* tool in the *Hydrology* toolbox in ESRI's ArcGIS Desktop 10.5.1 is used to remove any imperfections (sinks) in the DEM. A **sink** is a cell that does not have an associated drainage value. Drainage values indicate the direction that water will flow out of the cell and are assigned during the process of creating a flow direction grid for a given landscape. The resulting drainage network depends on finding the 'flow path' of every cell in the grid.

Step 2- Create a flow direction grid

A flow direction grid assigns a value to each cell to indicate the direction of flow –that is, the direction that water will flow from that particular cell based on the underlying

[19] Water Information System for Europe (WISE)

[20] The Water Framework Directive (WFD)

topography of the analysed landscape. This is a crucial step in hydrological modeling, as the direction of flow will determine the ultimate destination of the water flowing across the surface of the land.

Flow direction grids are created using the *Flow Direction* tool in ESRI's ArcGIS Desktop 10.5.1. For every 3x3 cell neighbourhood, the grid processor finds the neighbouring cell with the lowest value from the centre. These numbers have no numeric meaning –they are simply codes that define a specific directional value, and are determined using the elevation values included in the DEM.

Step 3 - Create a flow accumulation grid

The *Flow Accumulation* tool in ESRI's ArcGIS Desktop 10.5.1 calculates the water flow into each cell by identifying the upstream cells that flow into each downslope cell. In other words, each cell's flow accumulation value is determined by the number of upstream cells flowing into it as a function of the landscape topography. Cells with higher flow accumulation values should be located in areas of lower elevation, such as valleys or drainage channels where water flows naturally while it is following the landscape.

Step 4 - Create outlet (pour) points

Pour point placement is an important step in the process of watershed delineation. A pour point should exist within an area of high flow accumulation because it is used to calculate the total contributing water flow to that given point. In many cases, files containing the locations of the desired pour points are available, whether they are sampling sites, hydrometric stations, or another data source. Pour points may be created manually or by *Snap Pour point* tool in ArcGIS Desktop 10.5.1 using the flow accumulation grid.

Given the information about the watershed outlet, the tool performs two tasks: it snaps the pour point/s to the closest cell of high flow accumulation to account for any error during placement, and it converts the pour points to raster format for input to step 6.

Step 5 - Delineate watersheds

In ArcGIS Desktop 10.5.1, the *Watershed* tool creates the watershed having as outlet point the one delineated by the *Snap pour point* using the information given by the flow direction grid.

To estimate the water availability for each power plant, these steps were iteratively implemented for delineating each sub-basin conveying water to each plant. The outlet point of the sub-basin of each considered plant was identified and placed on the river network. The assumption behind this procedure is that the basin outlet position along the river network is located in the close surrounding area of the position of the power plant or where the power plant canals withdraw water. This assumption is meaningful due to the low resolution of the LISFLOOD model (used as source of observation of discharge when calibrating the HBV models), which has 5-km-length cells.

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Even though water and power systems are highly interdependent, currently those systems are seldom planned and managed together. This prevents us from taking advantage of synergies between the systems and leads to underestimation of risks involved.

This study is a model-based analysis of the impact of climate change on water availability and water temperature for the power system and its functioning; for this purpose, a hydrological (HBV) and two power system models (PRIMES-IEM and ENTIGRIS) were developed, adapted, and integrated.

The developed soft linkage of models maps future hydro-climatic projections into future power system operation, and allows to quantify the vulnerability of the power system to changes in the hydrological system due to climate change.

Water availability under different climate change scenarios was provided to the energy models to test the resilience of the future power system under changed climatic conditions. The study has analysed three macro-regions in Europe: the Iberian Peninsula, the Danube river basin and the Alpine region with a focus on Switzerland. A further micro-region study of the Adda river basin performed a soft-linkage between the two system models (hydrological and power system) to analyse feedback loops and mimic real time performance.

Results show that climate change and renewable energy penetration will have significant and diverse effects on the reliability and vulnerability of the energy system in the different regions also impacting energy prices.

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