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The water-power nexus of the Iberian Peninsula power system

WATERFLEX project

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The water-power nexus of the Iberian Peninsula power system – WATERFLEX project

Water availability influences power generation and its costs. Policies aimed at keeping the water stress index of thermal power plants within acceptable limits are needed. This report provides a model-based analysis of the water-power nexus in the Iberian Peninsula.

Contents

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Authors

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Executive summary

Traditionally, the water and energy sectors have been separately planned and operated. However, several international organisations such as the European Commission's Joint Research Centre (JRC) or the United States Department of Energy (DOE), among others, have raised awareness about the relevance of the water-energy nexus and its analysis as an integrated system. One of the aspects of the complex inter-dependencies of the water-energy nexus is the water-power (or water-electricity) nexus, which is the analysis and quantification of the water and electricity linkages within the electric power system.

This report presents an analysis of the water-power nexus in the Iberian Peninsula mainly because of its drastic hydrological differences across its territory, its little electrical interconnection with neighbouring territories, and the recent events of droughts and climate change impacts on the power sector.

Such analysis is carried out through an interdisciplinary modelling framework (decoupled and offline) including the link of the LISFLOOD rainfall-runoff hydrological model and the Dispa-SET power system model within the WATERFLEX project. This allows us for an in-depth assessment of the water implications on the power system operation and economics, the power implications on the water resources, a vulnerability analysis to water scarcity and the effect of cooling-related constraints from a policy perspective.

Policy context

This work has been conducted as a part of WATERFLEX ('Water Resources Providing Flexibility to the European Power System'), which is a joint exploratory research project within the European Commission's JRC. This work aims at supporting future impact assessments and communications related to the Energy Union Actions (COM(2015) 80, COM(2015) 6317, and COM(2014) 15).

According to the impact assessment SWD(2016) 410 final, '*extreme weather events are likely to affect the power supply in various ways*'. In fact, water impacts on European power systems have recurrently occurred in the last years and they led to monetary losses, power curtailments, temporary shutdowns, demand restrictions, and ultimately increased wear and tear of the power plants. These consequences call for an integrated framework of water and power sectors capable of analysing such water and power interactions.

Main findings

The proposed framework provides a sound and detailed analysis of the interactions between the water and power systems while identifying vulnerable thermal power plants. The main findings are listed as follows:

- The water value per catchment with a daily temporal resolution could be used for making informed decisions in the short-term operation of the power system.
- Water shortages (low flows) or policy decisions due to water restrictions could modify the available maximum capacity of certain water-stressed power plants, thus leading to system-wide generation cost increases or even shifting the water stress index to other power plants. Therefore, a global policy (or coordinated strategy) should be taken into account to keep the water-stress index of all thermal power plants within limits imposed due to policy restrictions or physical limitations.
- Water stress index could be endogenously taken into account in the unit commitment model providing less costly dispatch and commitment solutions while satisfying certain water stressed limits.
- A global policy to keep the water stress index within adequate (policy or physical) levels lead to generation cost increases.

Related and future JRC work

The framework proposed in this work will be used for performing similar analyses within the 'Water-Energy-Food-Ecosystem (WEFE) Nexus'. The geographical scope of the models will be Europe and Africa. The models and methods will be improved and the water and power interactions will be analysed under future climate scenarios.

Quick guide

The report first motivates the need for an integrated assessment of water and power sectors and then briefly presents the water and power systems for the Iberian Peninsula. Given an interdisciplinary modelling framework including the link of the LISFLOOD rainfall-runoff hydrological model and the Dispa-SET power system model, the report outlines the input data, main assumptions, as well as the definition of hydrological scenarios. Subsequently, an in-depth assessment of the water implications on the power system operation and economics, the power implications on the water resources, a vulnerability analysis to water scarcity and the effect of cooling-related constraints from a policy perspective is presented.

1 Introduction

1.1 Motivation

The water-energy nexus is the term used to refer to the complex interactions between the water sector and the energy sector [1], [2]. On the one hand, water is needed for energy production, fossil-fuel extraction, transport and processing, or irrigation purposes. On the other hand, energy is needed for extraction, treatment, and distribution of drinking water, and for wastewater treatment and desalination [1]. One aspect of this conundrum is the link between the water and the electric energy (also known as water-power nexus or water-electricity nexus) when it comes to its quantification within the electric power system [3]–[5].

Within the electricity sector context, the operation and economics of the power systems are constrained by the availability and temperature of water resources since thermal power plants need water for cooling and hydropower plants are fuelled by water to generate electricity. Regarding the thermal power plants, the largest amount of freshwater withdrawals for cooling purposes can be found in North America and Europe representing 86 % of the global water withdrawals [6], while the water used for cooling represents 43 % of the European Union's water demand [6], [7]. Due to water shortages or high river water temperatures, '*the number of days with a reduced useable capacity is projected to increase in Europe and USA*' according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [8]. In fact, water impacts on European power systems have recurrently occurred in the last years and they led to monetary losses, power curtailments, temporary shutdowns, demand restrictions, and ultimately increased wear and tear of the power plants (see [9] and references therein). On the other hand, the operation of the power system may impact on the quantity and quality of the water resources. This bidirectional analysis of the water-power nexus is crucial in the Iberian Peninsula for several reasons:

- Drastic hydrological differences can be found across its territory [10].
- Its pool-based electricity market is common for both countries (Spain and Portugal) comprising the Iberian mainland [11].
- It behaves as an electrical island [12] with around 3.5 % of the peak demand in Spain of electrical interconnection with France.
- Hydropower accounts for roughly one fifth of the total installed capacity [13], [14].
- Recent events of water scarcity in the Iberian Peninsula in 2017 [15]. As pointed out in the Greenpeace report [15], one third of the land in Spain, the most arid country of Europe, could be threatened by desertification. This phenomenon is strongly linked to the droughts and mainly affects to the centre and south of Spain as well as the Mediterranean coast. The droughts have a serious impact on agriculture, environment, ecosystems, drinking water supply and energy.
- Recent climate change impacts on the Iberian power sector cause a drastic reduction in hydropower production and, as a consequence, rising of CO_2 emissions and electricity prices [15], [16]. For instance, heat waves resulted in price peaks in Spain in July 2015 due to a high demand of air conditioning [17]. Moreover, the 2017 drought reduces hydropower output and increases generation from coal-fired power plants, increasing CO_2 emissions by 50% ([1]); and it reduces hydropower generation to the minimum in the historical record (since 1990) ([2]).

([1]) https://www.elconfidencial.com/economia/2017-07-11/contaminacion-emisiones-co2-elctricidad-carbon-hidraulica_1412809/

([2]) https://www.elconfidencial.com/economia/2017-11-01/sequia-hidraulica-octubre-minimo-agua-electricidad_1470330/

1.2 Literature review

In the last decade, the water-energy nexus has become a popular research topic worldwide. In 2012, the International Energy Agency (IEA) included a special chapter in the Word Energy Outlook 2012 (WEO-2012) highlighting the dependence of energy on water and its counterpart, i.e. water on energy, in a future water-constrained world [18]. This topic was further addressed in a full chapter within the WEO-2016 [1]. Also in 2012, the Energy-Water Nexus Crosscut Team was formed to address the issues associated with this nexus and, in 2014, the United States Department of Energy (DOE) published the report titled '*The Water-Energy Nexus: Challenges and Opportunities*' [19], which led to six roundtable discussions among industry, academia, utilities, government, and other stakeholders in 2015 (3). The Institute for Advanced Sustainability Studies (IASS) published a policy brief in February 2016 about the need for incorporating water constraints on the power system in order to secure a sustainable electricity supply [20]. On 28-29 September 2016, the DOE and the European Commission's Joint Research Centre (JRC), in cooperation with the Directorate-General for Research and Innovation, organised a workshop for understanding one of the aspects of the water-energy nexus, namely the integrated water and power system modelling. In this workshop, over 70 scientific experts, government officials and stakeholders, representatives of international organisations and industry took part to discuss such issues during the two-day event (4). In February 2017, the Midwest Energy Research Consortium (M-WERC) and the Water Council published a roadmap of the water-energy nexus by highlighting its market potential and opportunities [21]. Also, in September 2017, the Organisation for Economic Co-operation and Development (OECD) (5) published a new report to analyse the biophysical and economic consequences by 2060 of policy inaction regarding the lack of water, energy and land [22]. This report pointed out the main bottlenecks among the sectors from both economic and policy (on welfare, environment, food, water and energy security) perspectives. These are some examples to emphasise the increasing attention paid to the water-energy nexus in different organisations worldwide.

Apart from the international relevance of the water-energy nexus, this topic has recently been studied in a wide variety of dimensions across regions and geographic scopes, time scales, linking sectors or type of studies [9], [23]–[34]. In terms of regions, this complex link has been analysed in Europe [9], [23]–[28], United States [29], [30], China [31]–[33], or Middle East and North Africa (MENA) [34], always with an emphasis on arid or water scarce locations.

In United States, Scanlon *et al.* [29] and DeNooyer *et al.* [30] carried out quantitative analyses of the water-energy nexus at state level for Texas and Illinois, respectively. Scanlon *et al.* [29] focused explicitly on the 2011 drought year and analysed the effect on the power demand and the power plants' vulnerability regarding the 2010 non-drought year. DeNooyer *et al.* [30] analysed the economic and policy implications on two different scenarios for Illinois: 1) when shifting from coal to natural gas, and 2) when shifting from open-loop cooling technologies to closed-loop ones.

China has recently become a popular target for the holistic analyses of the interdependencies between water and energy in different sectors at a local [31], national [33], or even international level [32].

The MENA region which comprises the regions spanning from Morocco to Iran (in total 20 countries) was the focus in [34]. This paper quantified the water consumption in some energy-related activities and the energy intensity in some water-related activities and discussed both energy and environmental implications for that region.

Within Europe, the water needs in the Greek electricity sector and electricity consumption in the Greek water sector was evaluated in [24], [25]. The water-power nexus of Greece

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(3) Further information about the current and planned work by the United States DOE can be found in https://www.energy.gov/under-secretary-science-and-energy/energy-water-nexus-crosscut

(4) https://ec.europa.eu/jrc/en/news/exploiting-modelling-better-address-issues-related-water-energy-nexus

(5) http://www.oecd.org/about/

with high temporal and spatial resolution was studied in [9], as similarly done in part by this work for the Iberian Peninsula case study. Also, the vulnerability of electricity generation to climate change was examined at a basin level across European Union in [28]. Although Behrens *et al.* [28] were able to identify water-stressed regions at European level, the authors also recognised the lack of data about thermal power plants, the need for a higher temporal resolution, and the inclusion of a power dispatch model.

Regarding the Iberian Peninsula, Hardy *et al.* [23] were pioneering in analysing the water-energy links in different sectors including water, energy, irrigation, to name a few, at a national level for Spain. Specifically, they studied both the energy needed for the water use cycle including irrigation, and the water needs of the energy sector with special attention paid to biofuels. Moreover, this paper called for an integrated assessment of the water-energy nexus due to its complex inter-dependencies. Recently, several power and water co-optimization models with hourly time steps were proposed in the short-term by Santhosh *et al.* [35]–[38]. However, they were applied to hypothetical small case studies. From a different temporal resolution but greater geographic scope, the water-power nexus has been thoroughly studied in the Iberian Peninsula [3], [39]–[43]. A joint water-power optimisation framework was put forward in [3], [39], [40], [42], [43]. The framework relied on a stochastic approach based on either Stochastic Dynamic Programming (SDP) or Stochastic Dual Dynamic Programming (SDDP). Pereira *et al.* [3] recognised that further analysis of the water-energy nexus should be carried out such as the impact of cooling constraints or the effect of carbon capture and storage projects on river discharge; but they would require a higher spatial disaggregation. Bertoni *et al.* [41] focused on the incorporation of thermal cooling constraints within a deterministic approach (with weekly time steps) and its analysis for a control and climate change scenario was based on costs, water values, irrigation deficits, and water withdrawals of thermal power plants. Khan *et al.* [26] presented an integrated water-energy investment planning for analysing investment decisions in the Iberian Peninsula under two scenarios: a water-constrained energy system and an unconstrained energy system. This paper also highlighted the limited availability of data, which is one of the main challenges when it comes to the water-energy (or water-power) nexus' assessment.

Finally, Khan *et al.* [27] itemised the relevant aspects about the importance of an integrated water-energy nexus and pointed out some barriers on achieving such integrated system. This paper also provided some recommendations such as the spatial and temporal disaggregation of the nexus, the modelling of multipurpose reservoir hydropower plants, the inclusion of hydro-economic modelling to account for water scarcity, the analysis of water values, the incorporation of cooling- and policy-related constraints, or the harmonisation of input datasets across sectors when performing future climate change scenarios. As a part of this work, this report intends to address several of these recommendations and further work on other aspects is presented in Chapter 6.

1.3 Aim

The main goal of this report is to analyse the water-power nexus of the Iberian Peninsula case study with a high temporal and spatial resolution and with the most accurate data. Specifically, this work aims:

- To collect accurate data for Spain and Portugal from publicly available sources.
- To apply the framework presented in [44] to analyse the water-power nexus of the Iberian Peninsula power system. In this framework, we first run simulations from the Dispa-SET Medium-Term Hydrothermal Coordination (Dispa-SET MTHC) model [44] by taking into account water inflows given by the rainfall-runoff hydrological LISFLOOD model [45]. Then, the reservoir levels are passed on to the Dispa-SET Unit Commitment and Dispatch (Dispa-SET UCD) module [46], which runs for one year at hourly time steps.

- To perform a scenario-based analysis of the water and power interactions in the Iberian Peninsula power system.
- To analyse the impact of water availability on the Iberian power system operation and economics as well as the impact of the Iberian power system operation on water. Specifically, the water value per catchment is examined and water-stressed power plants are identified for different historical hydrological scenarios.
- To perform a vulnerability analysis of cooling-constrained power plants of the Iberian Peninsula based on limitations on the maximum allowable water withdrawn by those power plants.
- To analyse the effect of cooling-related constraints, which explicitly take into account the water stress index, in the Iberian Peninsula power system.

1.4 Layout

This report is divided in six chapters and three annexes. Chapters 2 and 3 briefly present both the water and power systems of the Iberian Peninsula. Chapter 4 describes the case study and the main assumptions on prices, generation mix, and aggregated plants, among others. This chapter also explains how the scenario-based analysis was performed. Chapter 5 presents the results from the Dispa-SET model (Dispa-SET MTHC and Dispa-SET UCD). It also discusses the vulnerability of cooling-constrained power plants to water scarcity and the effect of cooling-related constraints due to policy reasons or physical limitations. Finally, conclusions and future work are duly drawn in Chapter 6.

Annex 1 includes the techno-economic parameters of the main power plants of the Iberian Peninsula. Annex 2 presents the water inflows. Finally, Annexes 3 and 4 show additional results from the simulations.

2 Iberian Peninsula water system

2.1 Regulatory framework of the Spanish water system

The Ministry of Agriculture and Fisheries, Food and Environment (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente*), also known as MAPAMA, is the authority responsible for legislation and planning on water resources among other activities related to fishery, agriculture, and food industries ([6]). Water administration in the Spanish part of the Iberian Peninsula is organised by River Basin Districts or catchments (*Confederaciones Hidrográficas*) ([7]) as displayed in Figure 1:

— Spanish territory of the Eastern Cantabrian River Basin District (*Cantábrico Oriental*).

— Western Cantabrian River Basin District (*Cantábrico Occidental*).

— Galicia-Coast River Basin District (*Galicia Costa*).

— Spanish territory of the *Miño-Sil* River Basin District (*Miño-Sil*).

— Spanish territory of the *Duero* River Basin District (*Duero*).

— Spanish territory of the Tagus River Basin District (*Tajo*).

— Spanish territory of the *Guadiana* River Basin District (Guadiana).

— *Tinto*, *Odiel* and *Piedras* River Basin District (*Tinto, Odiel y Piedras*).

— *Guadalquivir* River Basin District (*Guadalquivir*).

— *Guadalete* and *Barbate* River Basin District (*Guadalete y Barbate*).

— Andalusian Mediterranean Basin District (*C.M. Andaluza*).

— *Segura* River Basin District (*Segura*).

— *Jucar* River Basin District (*Júcar*).

— Spanish territory of the *Ebro* River Basin District (*Ebro*).

— Catalonia River Basin District (*C.I. de Cataluña*).

There are another 10 River Basin Districts: *Islas Baleares*, *Melilla*, *Ceuta*, *Lanzarote*, *Fuerteventura*, *Gran Canaria*, *Tenerife*, *La Gomera*, *La Palma*, and *El Hierro*; but in this work we are focused on the ones located in the Iberian mainland. 10 river basins in the Iberian Peninsula are cross-regional (including *Cantábrico Oriental*, which in turn includes *C.I. del País Vasco*), whereas 4 river basins are regional and thus they are managed by the corresponding Autonomous Community. In addition, 9 river basin districts are transboundary, i.e. countries sharing borders: 1) *Miño-Sil*, *Duero*, *Tajo* and *Guadiana* are shared with Portugal, 2) *Cantábrico Oriental, Ebro* and *C.I. de Cataluña* are shared with France, 3) *Ebro* is also shared with Andorra, and 4) *Ceuta* and *Melilla* are shared with Morocco ([8]).

Each River Basin Authority has its own River Basin Management Plan (*Plan Hidrológico*) for 2015-2021 which addresses the inventory of resources and water bodies, uses and demands, ecological flows, identification of protected areas, identification of significant pressures, environmental objectives, cost recovery of water services or even hydrological drought management; while complying with Directive 2000/60/EC ([9]), of the European Parliament and of the Council, of 23 October 2000, establishing a framework for the Community action in the field of water policy. However, part of the second River Basin Management Plan has been adopted only by 2017 ([10]).

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[6] http://www.mapama.gob.es/en/ministerio/funciones-estructura/

[7] http://www.mapama.gob.es/en/agua/temas/planificacion-hidrologica/planificacion-hidrologica/default.aspx

[8] http://ec.europa.eu/environment/water/water-framework/impl_reports.htm

[9] http://ec.europa.eu/environment/water/water-framework/index_en.html

[10] http://ec.europa.eu/environment/water/participation/map_mc/map.htm

Apart from the river basin management plans of each river basin district, Greenpeace report [47] provides an environmental overview of most of the river basins. Several geographical characteristics such as the catchment extension, total river length, main cities and rivers covered by the river basin, water resources and consumptions in hm^3/year, as well as water uses can also be found in [47]. An updated gross consumption (consumptive, i.e. the one it is consumed and not returned) can be found in the corresponding management plans for 2015, 2027 and 2033.

Figure 1. Catchments in the Spanish part of the Iberian Peninsula.

Source: MAPAMA.

For a better water use and management (11), Spain has around 1 300 dams distributed across its territory [15]. As can be seen in Table 1, Spain has registered 1 063 large dams in ICOLD (International Commission on Large Dams) (12), thus occupying the ninth position of the top ten of number of dams by country member given by ICOLD, and the first country in Europe by number of dams. Table 2 shows the number of dams greater than 5 hm^3, the corresponding total reservoir capacity, and the relative capacity for each catchment (13). The total reservoir capacity is equal to 55 977 hm^3 at national level and 77.5 % corresponds to the reservoir capacity in the *Tajo*, *Guadiana*, *Guadalquivir*, *Ebro* and *Duero*.

Figure 2 illustrates the total reservoir capacity of each catchment and the reservoir levels during the year 2015 and is also divided into two groups depending on the coast where the water is discharged (either Atlantic or Mediterranean). Note that the total reservoir capacity refers to the water stored not only for generating electricity but also for other uses. Figure 3 shows the national reservoir level during 2015 in Spain. At the end of December 2015, the total reservoir level was above 50 % of its total capacity. However, we would like to point out the recent droughts due to low precipitation during 2017, which have led to a reduction of the national reservoir level below 40 % by 21 November 2017 (14). Figure 4 shows the relative reservoir level per catchment by 21 November 2017, wherein several catchments are below 50 % of its respective total capacity such as

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(11) http://www.sialtrasvase.com/la-realidad-hidrologica-de-espana/

(12) ICOLD is a non-governmental International Organization which provides a forum for the exchange of knowledge and experience in dam engineering.

(13) Information has been collected from http://www.mapama.gob.es/es/agua/temas/evaluacion-de-los-recursos-hidricos/boletin-hidrologico/

(14) http://www.mapama.gob.es/es/prensa/noticias/la-reserva-hidr%C3%A1ulica-espa%C3%B1ola-se-encuentra-al-37-por-ciento-de-su-capacidad/tcm7-472418-16

Galicia Costa, Miño-Sil, Ebro, Tajo, Guadiana, Guadalate-Barbate, Guadalquivir, C.M. Andaluza, Júcar and *Segura*. The last two even have a reservoir level less than 30 % (25 % and 13 %, respectively).

Table 1. Number of dams by country member.

Position	Country	Number of dams
1	China	23 842
2	United States of America	9 261
3	India	5 102
4	Japan	3 112
5	Brazil	1 411
6	Korea (Rep. of)	1 339
7	Canada	1 170
8	South Africa	1 114
9	**Spain**	**1 063**
10	Turkey	972
23	**Portugal**	**217**

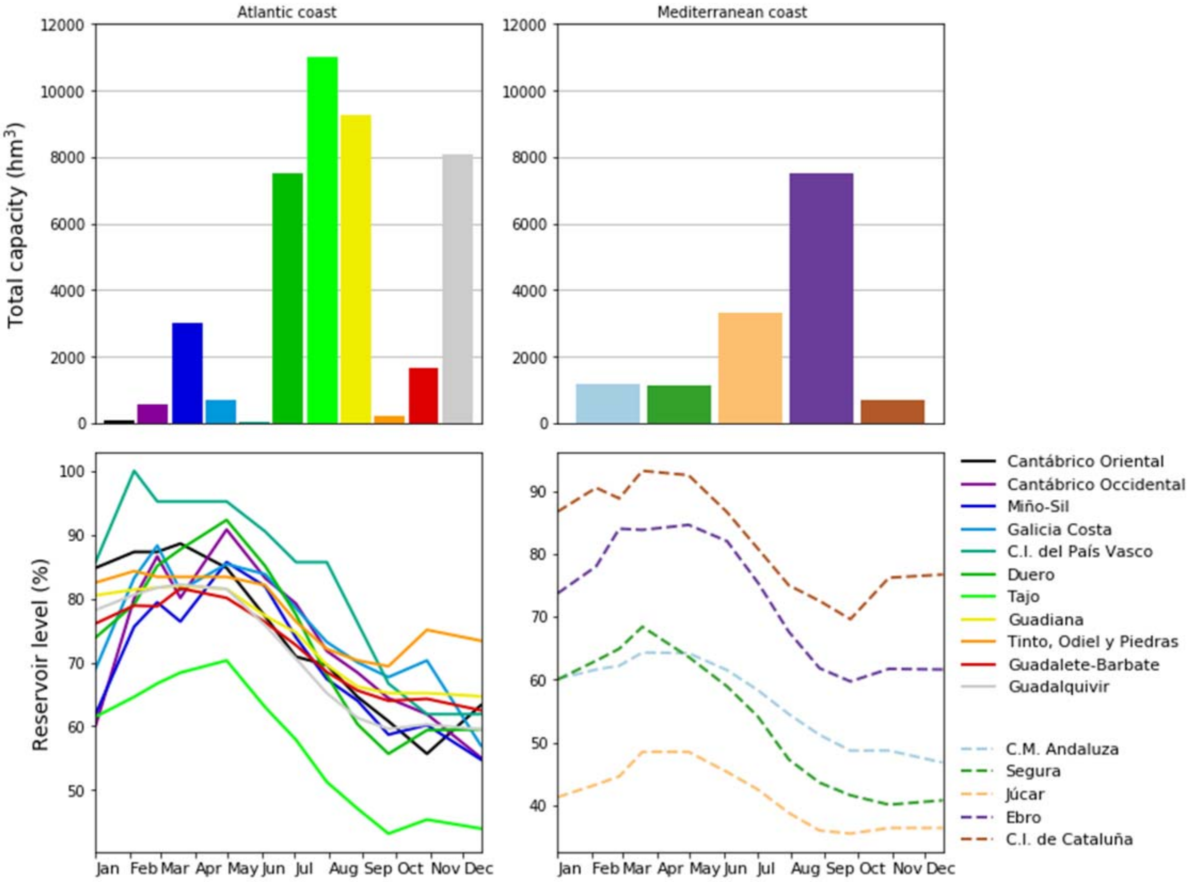
Source: ICOLD.

Table 2. Number of dams and total reservoir capacity per catchment.

Catchment	Number of dams (> 5 hm^3)	Total reservoir capacity (hm^3)	Capacity (%)
Tajo	51	11 012	19.7
Guadiana	36	9 266	16.6
Guadalquivir	46	8 101	14.5
Ebro	62	7 511	13.4
Duero	34	7 507	13.4
Júcar	23	3 337	6.0
Miño-Sil	29	3 030	5.4
Guadalete-Barbate	8	1 651	2.9
C.M. Andaluza	12	1 177	2.1
Segura	15	1 141	2.0
Galicia Costa	11	684	1.2
C.I. de Cataluña	7	677	1.2
Cantábrico Occidental	9	554	1.0
Tinto, Odiel y Piedras	7	229	0.4
Cantábrico Oriental	4	79	0.1
C.I. del País Vasco	2	21	0.0
Total	**356**	**55 977**	**100.0**

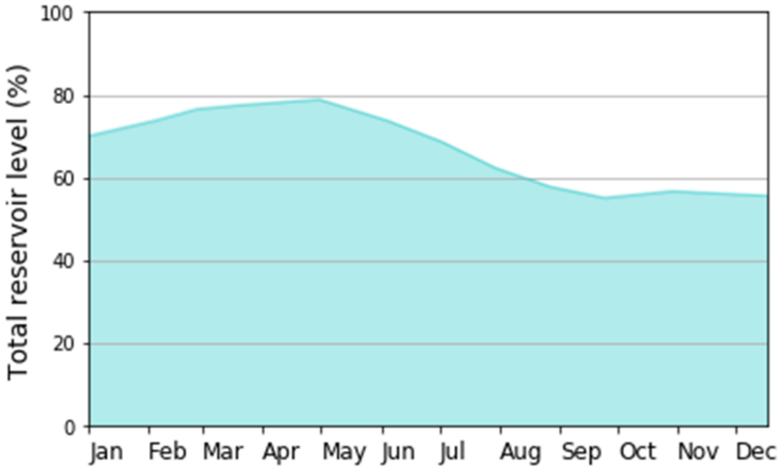
Source: MAPAMA.

Figure 2. Total capacity and reservoir levels per catchment in Spain during 2015. Left plots correspond to catchments discharging to the Atlantic coast and right plots correspond to catchments discharging to the Mediterranean coast.



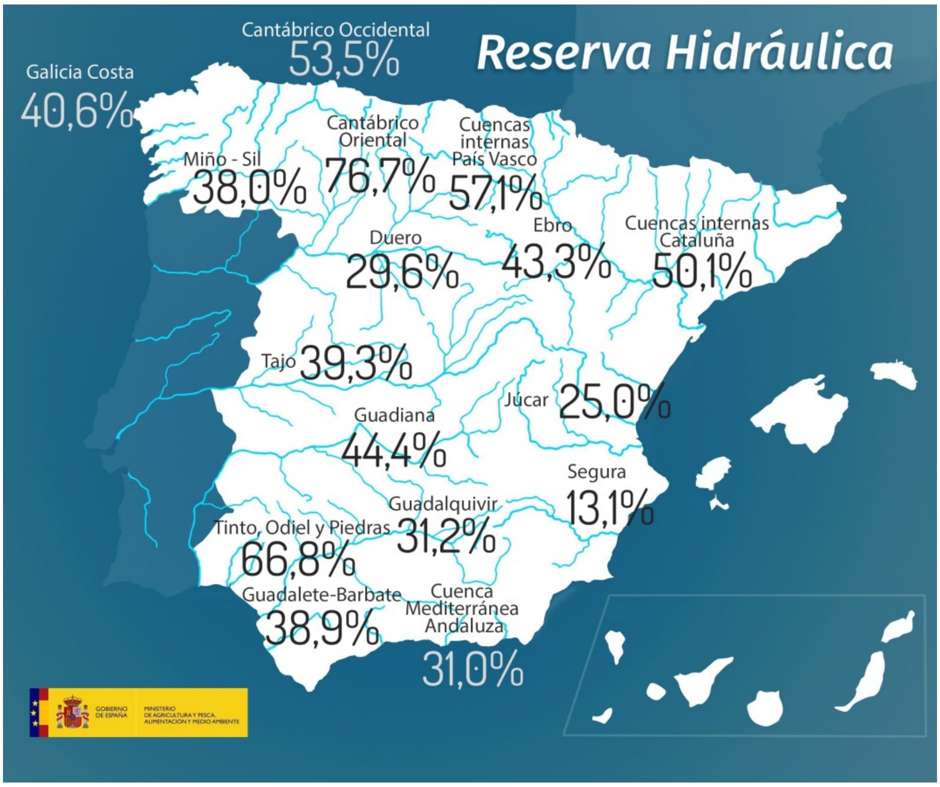
Source: MAPAMA, JRC 2017.

Figure 3. National reservoir level in Spain during 2015.



Source: MAPAMA, JRC 2017.

Figure 4. Spanish reservoir levels by 21 November 2017.



Source: MAPAMA.

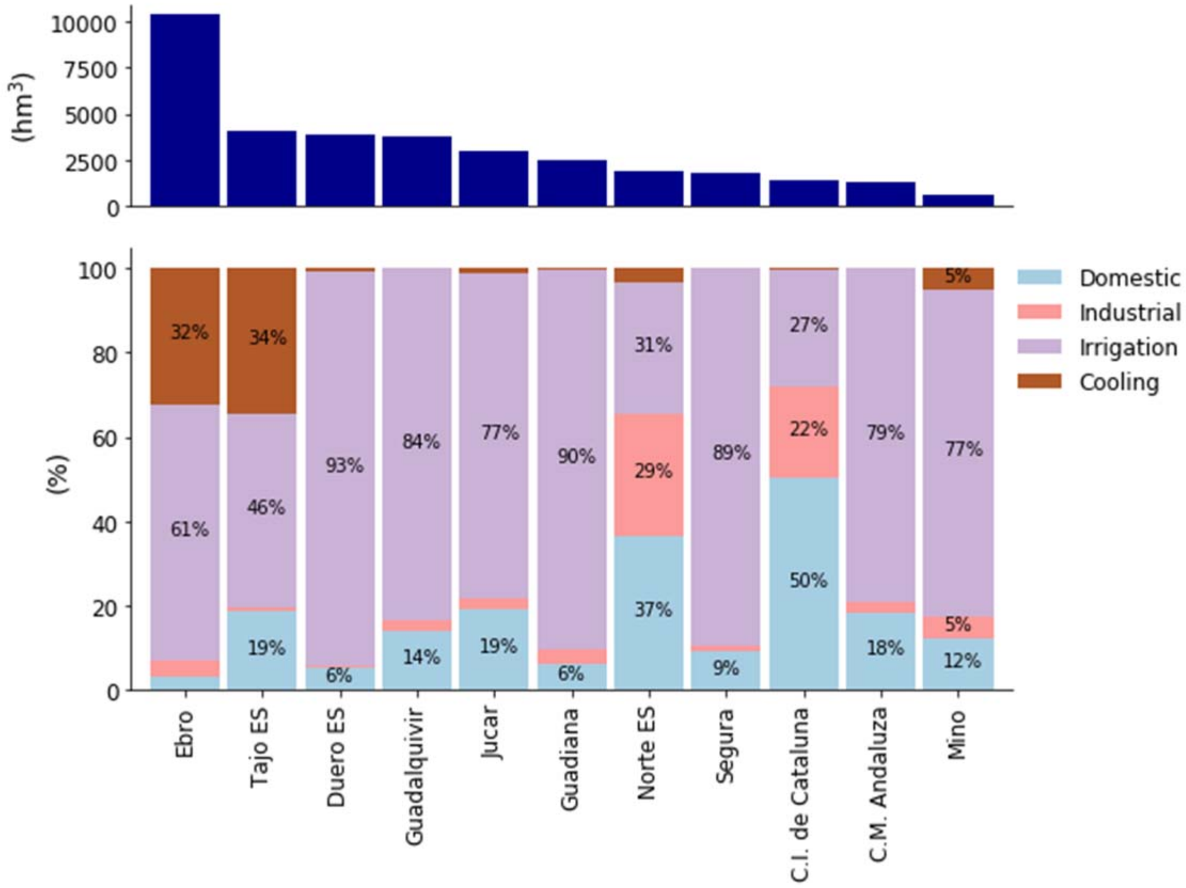
According to the Water White Paper of Spain [48], the total water demand in the Spanish part of the Iberian Peninsula amounted to 32 608 hm^3 in 2000. Figure 5 summarises the total water demand per catchment and the corresponding shares for four main purposes: domestic, industrial, irrigation, and cooling. Note that the greatest water demand user is the *Ebro* with more than 10 000 hm^3 followed by *Tajo*, *Duero* and *Guadalquivir* with a water demand around 3 800 hm^3. As can be observed, most of the water demand is devoted to irrigation in all catchments except for *Norte ES* and *C.I. de Cataluna* ([15]), wherein 37 % and 50 % is respectively devoted to domestic uses. We can also see that the major water demand for cooling can be found in the *Ebro* and *Tajo ES* as a consequence of the cooling of the following power plants:

— The nuclear power plants of *Asco* and *Santa María de Garoña* (this one has been already decommissioned) in the *Ebro*, whose respective water demands for cooling were 2 270 and 766 hm^3/year [48].

— The nuclear power plant of *Almaraz* and the coal power plant of *Aceca* in the *Tajo ES*, whose respective water demands for cooling were 583 and 544 hm^3/year [48].

([15]) The notation for the catchments and the relation with the actual ones can be found in Section 4.4.

Figure 5. Total water demand per catchment (upper plot) and share of water demand per purpose (lower plot).



Source: Water White Paper of Spain [48], JRC 2017.

For multipurpose reservoirs, water use priorities have been defined in general terms in BOE-A-2001-14276 ([16]) as follows, unless otherwise specified by the water management plan of their own River Basin Authority:

1. Domestic water supply.
2. Irrigation and agricultural uses.
3. Industrial uses for electricity production.
4. Aquiculture.
5. Recreational uses.
6. Navigational uses.
7. Other uses.

([16]) https://www.boe.es/buscar/doc.php?id=BOE-A-2001-14276

2.2 Regulatory framework of the Portuguese water system

The Ministry of Environment (*Ministério do Ambiente*) is one of the relevant authorities responsible for water resources management in Portugal. The Water Institute INAG (*INstituto da ÁGua*) and the Portuguese Environment Agency APA (*Agência Portuguesa do Ambiente*) are responsible for implementing water policy at national level ([17]). The INAG institute created the National Water Resources Information System SNIRH (*O Sistema Nacional de Informação de Recursos Hídricos*), which is in charge of both monitoring the water resources and disseminating hydro-meteorological and water quality data ([18]). Water administration in the Portuguese part of the Iberian Peninsula is divided into 8 river basin districts ([19]):

- The *Minho* and *Lima* River Basin District.
- The *Cávado*, *Ave* and *Leça* River Basin District.
- Portuguese territory of the *Douro* River Basin District.
- The *Vouga*, *Mondego*, *Lis*, and *Ribeiras do Oeste* River Basin District.
- Portuguese territory of the *Tejo* River Basin District.
- The *Sado* and *Mira* River Basin District.
- Portuguese territory of the *Guadiana* River Basin District.
- The *Ribeiras do Algarve* River Basin District.

Four river basin districts are transboundary (*Minho-Lima*, *Douro*, *Tejo* and *Guadiana*), i.e. they share water courses with Spain. There are also another two River Basin districts outside the Portuguese mainland, namely *Açores* and *Madeira*. Moreover, the above river basin districts can be divided into catchments (*Bacias Hidrográficas*) as displayed in Figure 6.

Each River Basin Authority has its own River Basin Management Plan (*Planos de Gestão de Região Hidrográfica*) for 2016-2021 while complying with Directive 2000/60/EC ([20]), of the European Parliament and of the Council, of 23 October 2000, establishing a framework for the Community action in the field of water policy. Unlike Spain, all second River Basin Management Plans were adopted by 2017 ([21]). Also it is important to point out that there are no joint River Basin Management Plans with Spain, although there is some coordination between them.

Finally, according to ICOLD, Portugal has 217 large dams distributed across its territory ([22]). As similarly done for Spain, Figure 7 illustrates the total reservoir capacity and the reservoir levels during 2015 of each Portuguese catchment whereas Figure 8 shows the national reservoir levels for 2015. Note that the total reservoir capacity refers to the water stored not only for generating electricity but also for other uses. The biggest reservoir capacities can be found for *Guadiana* and *Tejo*, and the total reservoir levels remained above 60 % at the end of December 2015.

([17]) http://www.apambiente.pt/index.php?ref=x178
http://www.protos.ngo/es/eureau-statistics-overview-water-and-wastewater-europe-2008

([18]) http://snirh.apambiente.pt/index.php?idMain=5&idItem=5

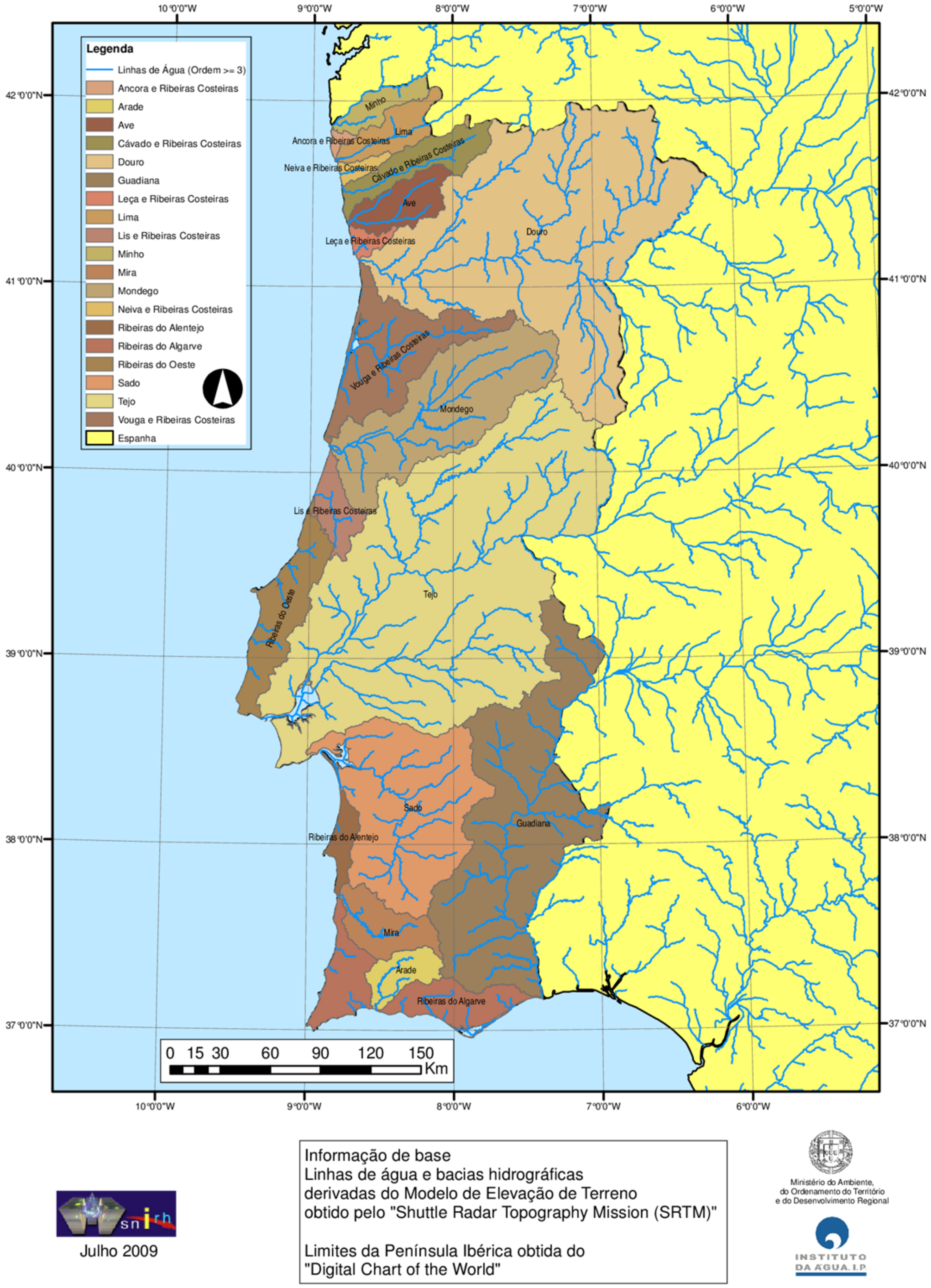
([19]) http://ec.europa.eu/environment/water/water-framework/impl_reports.htm

([20]) http://ec.europa.eu/environment/water/water-framework/index_en.html

([21]) http://ec.europa.eu/environment/water/participation/map_mc/map.htm

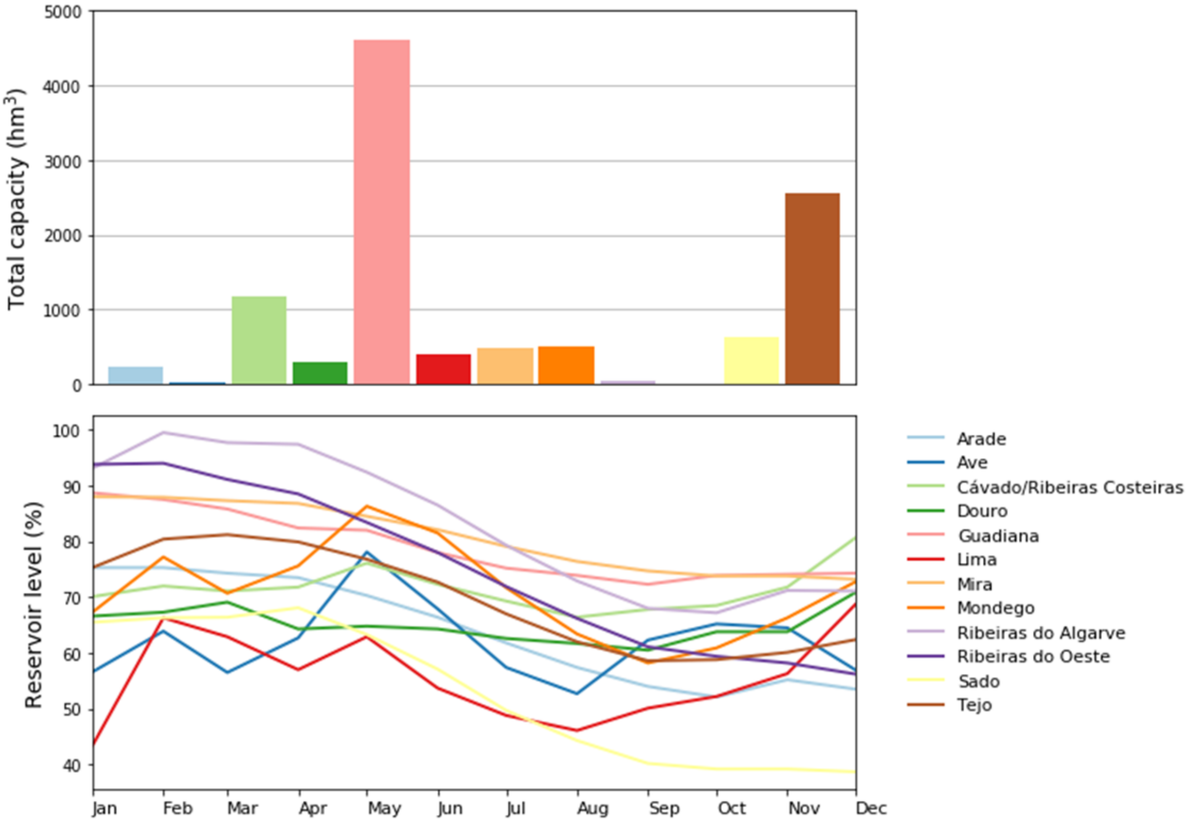
([22]) http://www.icold-cigb.net/article/GB/world_register/general_synthesis/number-of-dams-by-country-members

Figure 6. Catchments in the Portuguese part of the Iberian Peninsula.



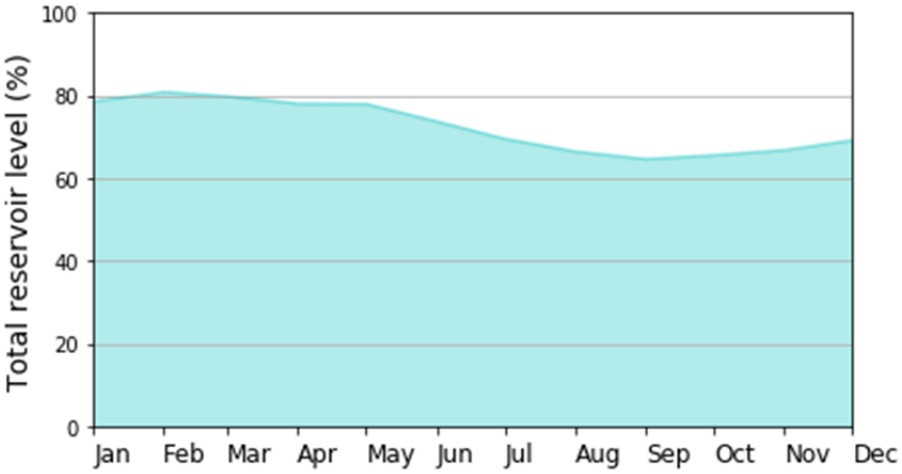
Source: Ministry of Environment of Portugal, INAG.

Figure 7. Total capacity and reservoir levels per catchment in Portugal during 2015.



Source: SNIRH, JRC 2017.

Figure 8. National reservoir level in Portugal during 2015.



Source: SNIRH, JRC 2017.

Table 3 presents a summary of annual water consumptions per sector based on the Portuguese National Water Plan [49]. It can be seen that the major water consumption is the agriculture sector, as happened also for Spain, with a relative water consumption of 75 %. The agriculture sector is followed by the water consumed in the energy sector which accounts for 14 % of the total annual water consumption.

Table 3. Total water demand in the Portuguese mainland.

	Annual water consumption (hm^3)	**Relative water consumption (%)**
Agriculture (irrigation)	6 551	74.8
Energy production	1 237	14.1
Public water supply	561	6.4
Industry	385	4.4
Tourism	20	0.2
Total	8 754	100.0

Source: INAG 2001, [49].

3 Iberian Peninsula power system

3.1 Overview of the current power system

The organisation of the power system in the Iberian Peninsula is market-based and most of the activities are regulated by a private ownership. The major market players are the market operator OMIE [50], which comprises both Spain and Portugal, and the system operators of Spain, REE (*Red Eléctrica de España*) [13], and Portugal, REN (*Redes Energéticas Nacionais*) [14].

Different markets are cleared within a daily framework such as the day-ahead market, intra-day markets, a reserve market, and balancing and adjustment markets [12]. The market operator OMIE is the entity responsible for the financial management of the market, whereas REE and REN are respectively the Spanish and Portuguese system operators responsible for the technical feasibility of the system from both generation and transmission perspectives. Futures markets, which are financial instruments to hedge risk, were set up for the Iberian Peninsula in 2007. The entity in charge of the Iberian futures market is MIBEL [51] and it '*would bring benefits to the consumers of both countries within a framework for providing access to all interested parties pursuant to the terms of equality, transparency and objectivity*' (23). In this work, we assume that the generators submit generation offers according to their corresponding marginal costs.

Since the analysis performed in this report is based on the year 2015, the generation fleet of the Iberian Peninsula power system is briefly explained next. Figure 9 represents the locations of the thermal and hydro power plants above 100 MW of the generation fleet available in 2015. These locations are represented across catchments (as previously mentioned, the Iberian Peninsula is made up to 23 catchments).

Figure 10 illustrates the installed capacity share of different technologies for the Iberian Peninsula. The total installed capacity is 100.6 GW for Spain and 18.5 GW for Portugal. As can be seen, fossil gas and wind onshore represents more than half of the total installed capacity in the Iberian Peninsula, followed by hydro run-off-river and water reservoir by 14.2 %. The total hydropower fleet amounts to 26 215 MW (22 % of the total installed capacity), which 77 % corresponds to Spain and 23 % to Portugal. The power system in the Iberian Peninsula has also high share of renewable facilities (solar and wind mainly). The solar and wind power capacity amounts almost to one third of the total installed capacity of the Iberian Peninsula. By 2015, the total wind onshore capacity is 22 828 MW for Spain and 4 826 MW for Portugal. However, fossil-fuel power plants have a high share in the generation mix (40.7 % including lignite, gas, hard coal, and oil); 42 GW are located in Spain whereas 6.5 GW are in Portugal. Finally, nuclear power plants are only located in the Spanish territory and represent 6.4 % of the generation mix.

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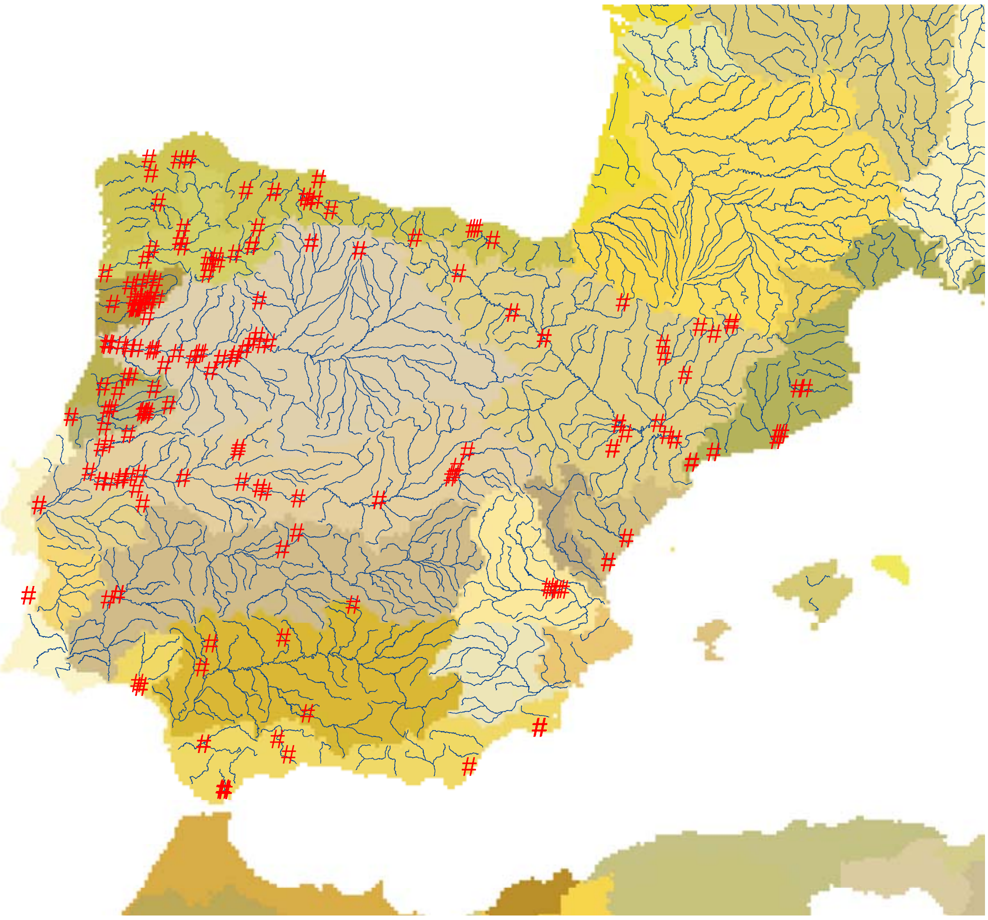
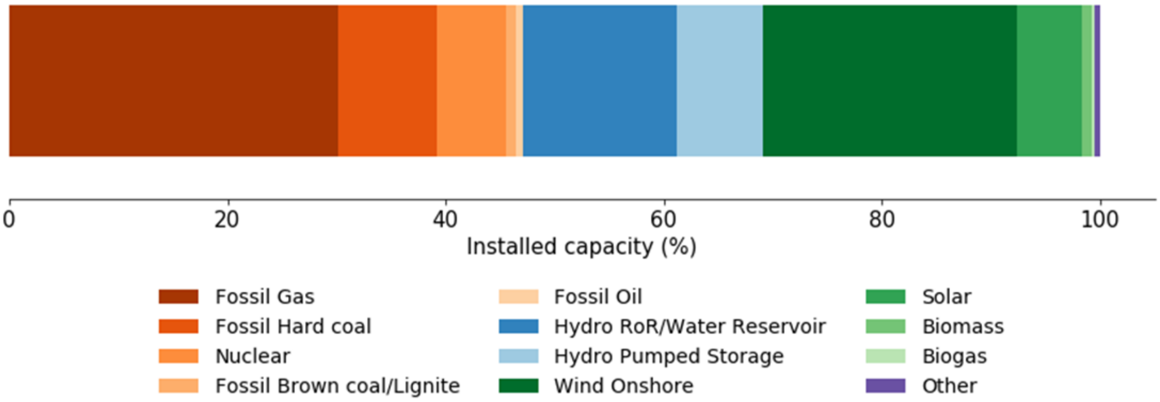
(23) http://www.mibel.com/index.php?mod=pags&mem=detalle&relmenu=9&relcategoria=1026&idpag=67

Figure 9. Iberian Peninsula's catchments with power plants above 100 MW.



Source: REE, REN, JRC 2017.

Figure 10. Installed capacity in the Iberian Peninsula for the year 2015.

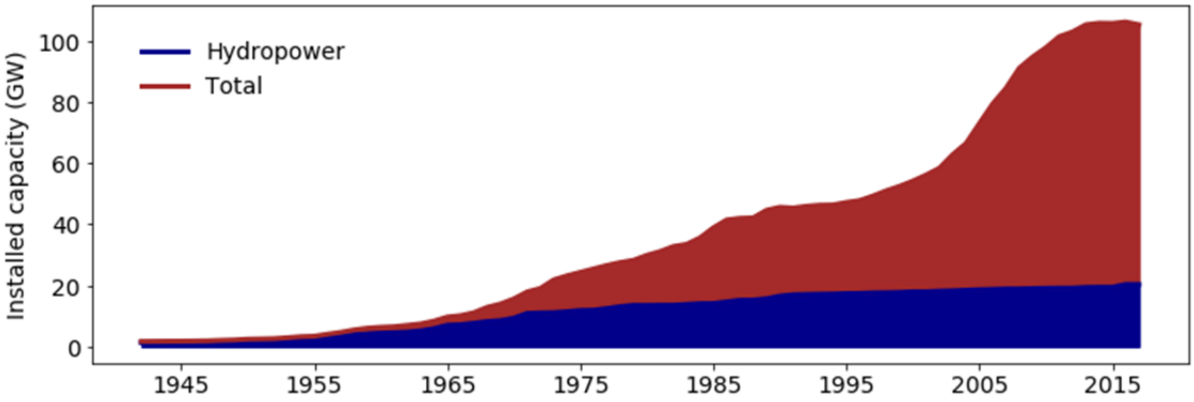


Source: REE, REN, JRC 2017.

3.2 Historical evolution of hydropower

Figure 11 shows the evolution of the installed hydropower capacity and its comparison over the total installed capacity from 1941 till 2016 in Spain [13], [52]. As can be seen, the hydropower capacity has decreased its share in the generation mix from 78% in 1941 to approximately 20% in 2016. In the last decade, the installed hydropower capacity has remained almost unchanged – it has been increased by 7.7 % – and thus representing around 20% of the total installed capacity in Spain.

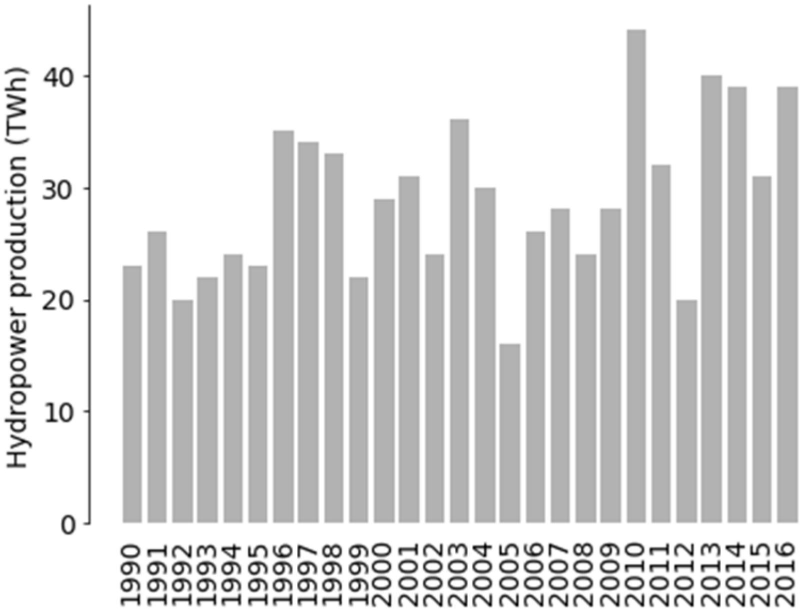
Figure 11. Evolution of installed hydropower capacity and total installed capacity in Spain.



Source: REE, [52].

The annual hydropower production is represented in Figure 12 from 1990 till 2016. The minimum generation can be found in the year 2005, whereas the maximum generation was reached in 2010. Although its production highly depends on hydrological conditions, the hydropower generation has relatively increased in the last years compared to values in the nineties because there has been an increase of 20 % of hydropower installed capacity in the last 26 years.

Figure 12. Annual historical hydropower generation in Spain.



Source: REE.

4 Input data and assumptions

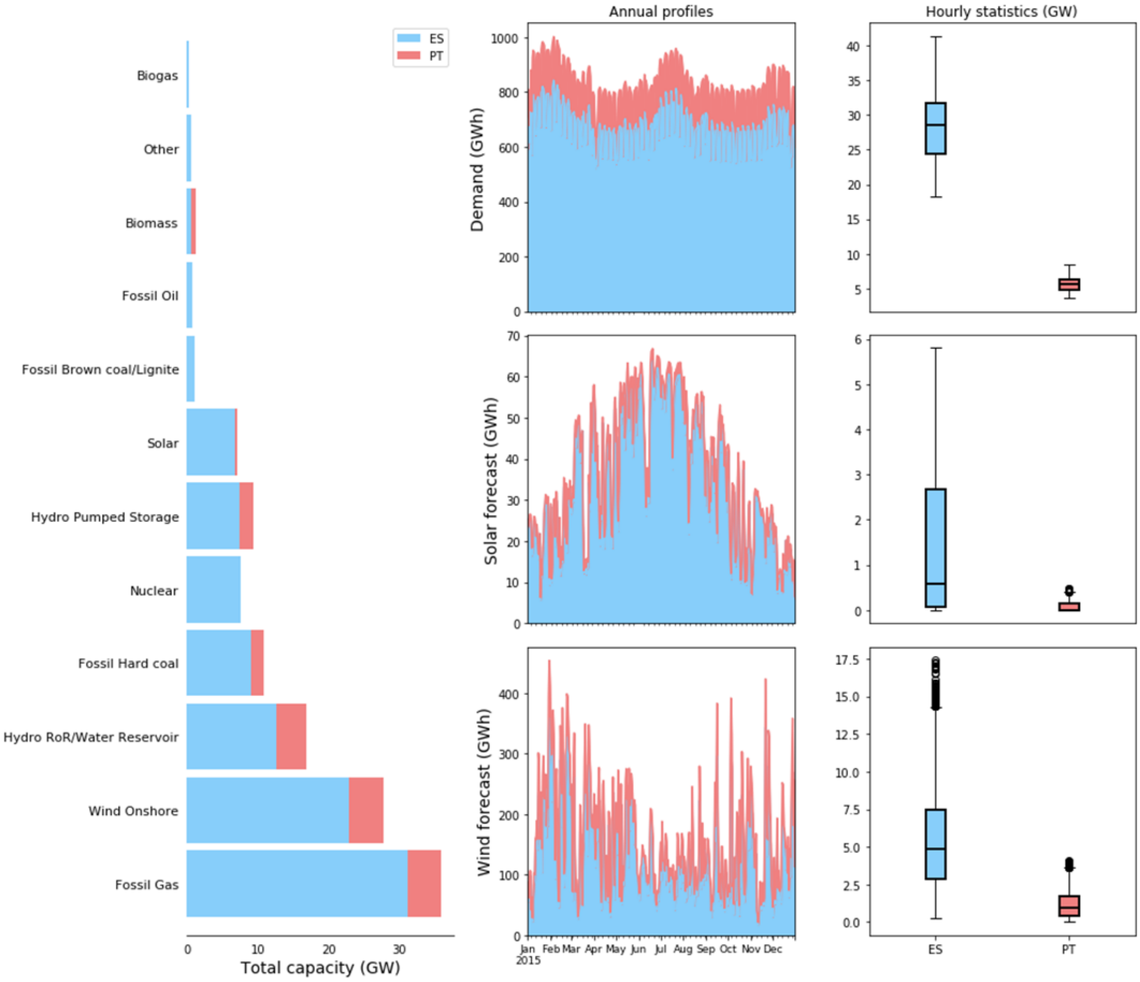
The framework presented in [44] is applied to the Iberian Peninsula power system to analyse the water-power nexus. In this framework, we first run simulations from a mid-term hydrothermal coordination model by using the Dispa-SET MTHC module [44]. Water inflows given by the rainfall-runoff hydrological LISFLOOD model [45] are taken into account. Then, the reservoir levels are passed on to a unit commitment problem which is simulated by using the Dispa-SET UCD module [46].

The input data of the Iberian Peninsula case study for the Dispa-SET MTHC and Dispa-SET UCD are set up as explained in the next sections. The simulation target year is assumed to be 2015. For Dispa-SET MTHC model, the optimisation horizon is set to two years with daily time steps in order to avoid border effects in the target year; therefore the model is run from 1 July 2014 till 30 June 2016. On the other hand, Dispa-SET UCD is sequentially run for one year with 7-day optimisation horizons, one-day look-ahead period and hourly time steps.

4.1 Demand and renewable profiles

The demand time series as well as the wind and solar profiles for Spain and Portugal in 2015 have been obtained through the ENTSO-E Transparency Platform [53]. Figure 13 shows the daily profiles for the demand, wind forecast, and solar forecast in GWh, and their corresponding hourly statistics; and the total installed capacity itemised by country (Spain is represented in blue and Portugal in red) and fuel type.

Figure 13. Installed capacity, demand and renewable profiles for the Iberian Peninsula in 2015.



Source: ENTSO-E, JRC 2017.

The maximum load peak is 41.4 GW for Spain and 8.5 GW for Portugal, which are less than half of the corresponding total installed capacities. Therefore, it is clear that there is an overcapacity in the Iberian Peninsula. The average hourly demand is around 28 GW and 6 GW for Spain and Portugal, respectively.

Regarding the wind forecast, the maximum peak reaches 76 % of the total installed wind capacity in Spain and 84 % in Portugal. On average, the wind facilities will be generating 5.5 GW in Spain and 1.2 GW in Portugal. The maximum peaks for the solar forecast are almost equal to the corresponding installed capacities whereas on average the solar facilities will generate 1.5 GW and 80.5 MW on average.

Note that all solar, wind, waste, and biomass facilities have been clustered in both the Dispa-SET MTHC and Dispa-SET UCD models.

4.2 Thermal power plants

The thermal fleet in Spain consists of 92 thermal power plants wherein there is a cluster for power plants fuelled by oil and another cluster for those with natural gas cogeneration. There are 52 gas units including the NG cluster, 28 hard coal power plants, 3 lignite power plants, and 8 nuclear power plants. However, the gas power plant *Gibraltar-San Roque* and the nuclear power plant *Santa María de Garoña* were unavailable during 2015; therefore we have assumed a zero maximum capacity. Information about Spanish power plants has been collected from REE [13].

The thermal fleet in Portugal consists of 15 thermal power plants: 10 gas power plants (one of them is a cluster which amounts to 782.8 MW), and 5 hard coal power plants. Information about Portuguese power plants has been collected from REN [14].

In the Dispa-SET MTHC model, power plants have been clustered by country and fuel type giving rise to 17 clusters (precluding the hydro power plants' cluster). Table 4 shows the capacity assumed for each of them.

In the Dispa-SET UCD model, more technical parameters are needed for running simulations since it accounts for inter-temporal constraints or cooling system constraints, among others [44], [46]. Annex 1 provides the techno-economic features of all units including the thermal generators: Table 10 shows the country where each unit belong to, its technology and fuel type, the corresponding capacity, the minimum generation level in percentage with respect to the capacity and the efficiency; Table 11 includes the minimum up and down times, ramp up and down rates, start-up costs, minimum efficiencies, start-up times, and CO_2 intensity; and Table 12 collects the withdrawal factor (24) of each power plant based on the average factors provided in [54].

According to Platts [55], [56], of 103 thermal power plants in the Iberian Peninsula, 42 % use once-through cooling technologies (19 power plants take fresh water whereas 24 power plants take sea water), 45 % use wet cooling towers (31 power plants with mechanical draft cooling towers and 15 with natural draft cooling towers), and 6 % and 4 % use combined cooling systems and dry cooling, respectively.

In addition, the following assumptions are adopted:

- The generating units or power plants submit generation offers according to their corresponding marginal costs.
- No planned or unplanned outages are assumed during the optimisation horizon in order to simplify the analysis of results which are focused on the water implications in the power system.
- The water consumption and withdrawal factors are based on the average values collected in [54].

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(24) Withdrawal factor can be defined as the amount of water withdrawn for cooling to generate one MW. Reference [54] provides water withdrawal factors per technology based on estimates of operational water withdrawal factors for electricity generating technologies in the United States.

- No-load and ramping costs are neglected.
- A value of 7.7 €/ton CO_2 is assumed for the price of the emission allowances throughout the year 2015 [55].

Table 4. Techno-economic features for all units excluding hydro power plants considered in the Dispa-SET MTHC.

(*Editor's note:* the notation can be found in the list of abbreviations and definitions)

Unit	Country	Type	Fuel type	Capacity (MW)
HRD ES cluster	ES	Thermal	HRD	9 090.0
GAS ES cluster	ES	Thermal	GAS	25 280.4
NUC ES cluster	ES	Thermal	NUC	7 572.4
LIG ES cluster	ES	Thermal	LIG	1 055.7
BGAS ES cluster	ES	Biogas	BGAS	255.9
WIND ES cluster	ES	Wind	WIND	22 828.1
SUN ES cluster	ES	Solar	SUN	6 719.9
OIL ES cluster	ES	Thermal	OIL	736.0
BIOMASS ES cluster	ES	Biomass	BIOMASS	550.5
WASTE ES cluster	ES	Waste	WASTE	536.1
NG COGEN ES cluster	ES	Thermal	NG COGEN	5 877.0
HRD PT cluster	PT	Thermal	HRD	1 756.0
GAS PT cluster	PT	Thermal	GAS	4 698.0
WIND PT cluster	PT	Wind	WIND	4 826.0
SUN PT cluster	PT	Solar	SUN	429.0
BIOMASS PT cluster	PT	Biomass	BIOMASS	613.0
OTHER PT cluster	PT	Other	OTHER	347.3

Source: JRC 2017.

4.3 Fuel prices

The hourly price time series for biomass, hard coal, gas, nuclear and oil used in the Dispa-SET UCD model are illustrated in Figure 14. Biomass, hard coal, gas, and oil daily prices are obtained from Platts [55], whereas uranium daily prices come from the International Monetary Fund (IMF) ([25]). Conversion to €/MWh is done by using adequate conversion factors and exchange rates from US dollars to €. Sometimes the time series are not complete and a proper interpolation is required to fill the gaps. Note that the average prices for biomass, hard coal, gas, uranium and oil are respectively 89.6, 7.3, 20.3, 0.5, and 19.0 €/MWh and they are used for the Dispa-SET MTHC model. We have assumed the same prices for Spain and Portugal. Finally, the lignite prices are assumed to be constant throughout the year and equal to 10.62 €/MWh.

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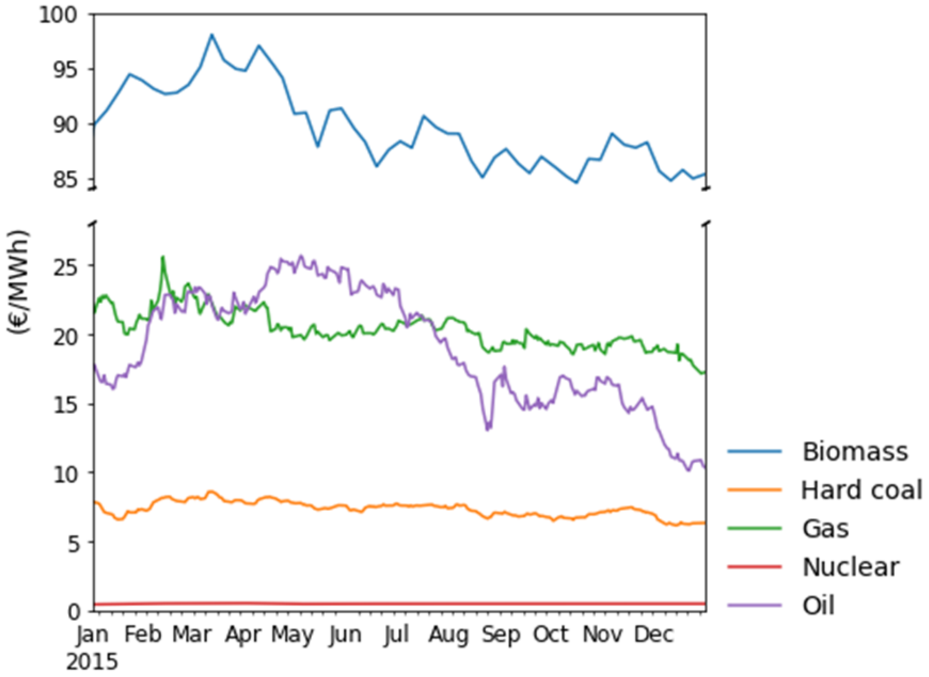
[25] http://www.imf.org/external/np/res/commod/index.aspx

Figure 14. Hourly prices for biomass, hard coal, gas, nuclear and oil in 2015.



Source: Platts, IMF, JRC 2017.

4.4 Hydropower plants

The hydropower fleet can be divided into hydropower reservoirs, run-of-river, and pumped hydro. The total hydropower installed capacity was 20 076 MW for Spain in 2015 with more than 1 000 units whereas it was 6 139 MW for Portugal with more than 60 units. In order to keep computational tractability and due to lack of data, the hydropower fleet per catchment was aggregated in an equivalent hydropower plant. The actual River Basin Districts associated with each cluster are shown in Table 5.

Table 6 shows the technical features assumed for each hydro equivalent unit: 1) the total installed capacity based on REE [13] and REN [14], 2) the maximum reservoir volume in hm^3 based on MAPAMA ([26]) or EDP ([27]), and 3) the minimum reservoir volume in hm^3. The equivalent net heads of the hydro equivalent units in Spain have also been estimated based on the values of capacity in GWh and hm^3 provided in MAPAMA. However, volume and head data for individual hydro power plants in Portugal can be collected from EDP, and therefore net heads are estimated based on EDP information. For the sake of comparison, Figure 15 represents the relationship between the net head, reservoir volume and installed capacity of each hydro equivalent unit. As can be seen, *Duero*, *Tajo* and *Ebro* in Spain present the main hydropower potential of the Iberian Peninsula.

Moreover, the following assumptions are adopted:

- The minimum power output is set equal to 40 % of the total installed capacity of the corresponding hydro equivalent unit.
- The minimum reservoir volume is set equal to 60 % of the maximum reservoir capacity.
- The hydro equivalent units are also assumed in the Dispa-SET UCD model for the sake of consistency, i.e. no further aggregation was made in the unit commitment model.

([26]) http://www.mapama.gob.es/es/agua/temas/evaluacion-de-los-recursos-hidricos/boletin-hidrologico/

([27]) http://www.a-nossa-energia.edp.pt/centros_produtores/producao.php?cp_type=he&map_type=he#mapContainer

— Water demands are accounted for in the computation of the net inflows.

— Ecological flows are neglected.

Table 5. Relationship between the hydro equivalent units considered in the Dispa-SET MTHC model and the actual River Basin Districts.

Hydro equivalent unit	**Country**	**Catchment(s)**
C.I. de Cataluna cluster	ES	*C.I. de Cataluña*
C.M. Andaluza cluster	ES	*C.M. Andaluza* *Tinto, Odiel y Piedras* *Guadalete y Barbate*
Duero ES cluster	ES	Spanish territory of *Duero*
Ebro cluster	ES	*Ebro*
Guadalquivir cluster	ES	*Guadalquivir*
Guadiana cluster	ES	Spanish territory of *Guadiana*
Jucar/Segura cluster	ES	*Júcar* *Segura*
Norte ES cluster	ES	*Galicia costa* *Cantábrico occidental* *Cantábrico oriental*
Mino cluster	ES	*Miño-Sil*
Tajo ES cluster	ES	Spanish territory of *Tajo*
Duero PT cluster	PT	Portuguese territory of *Duero*
Ribeiras south cluster	PT	*Sado* and *Mira* Portuguese territory of *Guadiana* Ribeiras do *Algarve*
Ribeiras north cluster	PT	*Minho* and *Lima* *Cávado, Ave* and *Leça*
Ribeiras central cluster	PT	*Vouga*, *Mondego*, *Lis*, and *Ribeiras do Oeste*
Tajo PT cluster	PT	Portuguese territory of *Tajo*

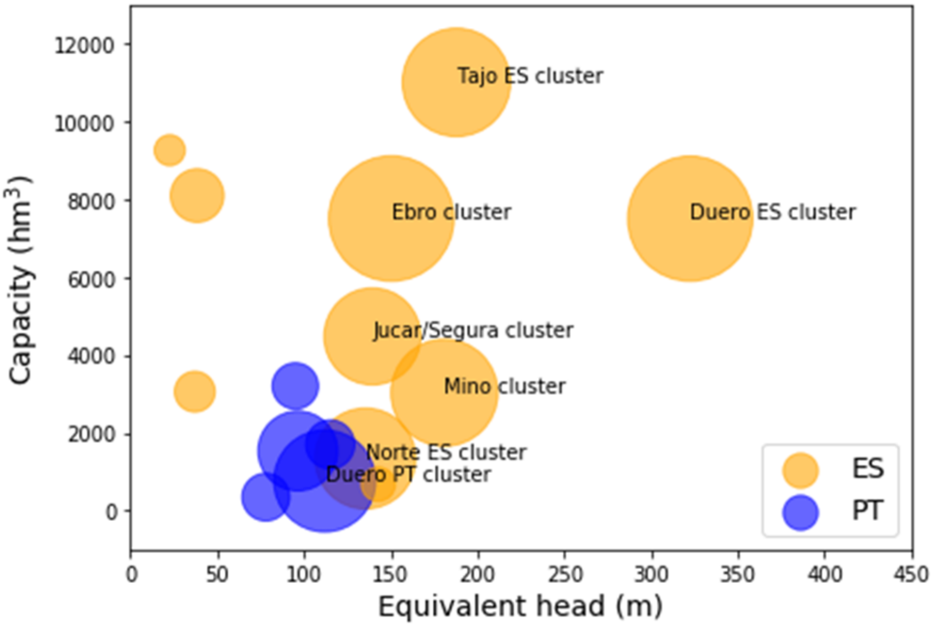
Source: JRC 2017.

Table 6. Technical features for the hydro equivalent units considered in the Dispa-SET MTHC.

Hydro equivalent unit	**Capacity (MW)**	**Minimum volume (hm^3)**	**Maximum volume (hm^3)**
C.I. de Cataluna cluster	288.9	406.2	677.0
C.M. Andaluza cluster	407.5	2 445.6	3 057.0
Duero ES cluster	3 892.4	4 504.2	7 507.0
Ebro cluster	3 912.6	4 506.6	7 511.0
Guadalquivir cluster	708	4 860.6	8 101.0
Guadiana cluster	235.2	5 559.6	9 266.0
Jucar/Segura cluster	2 336.2	2 686.8	4 478.0
Norte ES cluster	2 529.1	802.8	1 338.0
Mino cluster	2 851.1	1 818.0	3 030.0
Tajo ES cluster	2 915	6 607.2	11 012.0
Duero PT cluster	2 584.9	456.1	760.2
Ribeiras south cluster	529.6	1 922.4	3 204.0
Ribeiras north cluster	1 581.2	919.3	1 532.2
Ribeiras central cluster	565.9	207.8	346.3
Tajo PT cluster	595.1	1 019.9	1 699.8

Source: JRC 2017.

Figure 15. Reservoir water capacity, equivalent head, and electricity capacity per catchment. The electricity capacity is represented by the bubble's size.

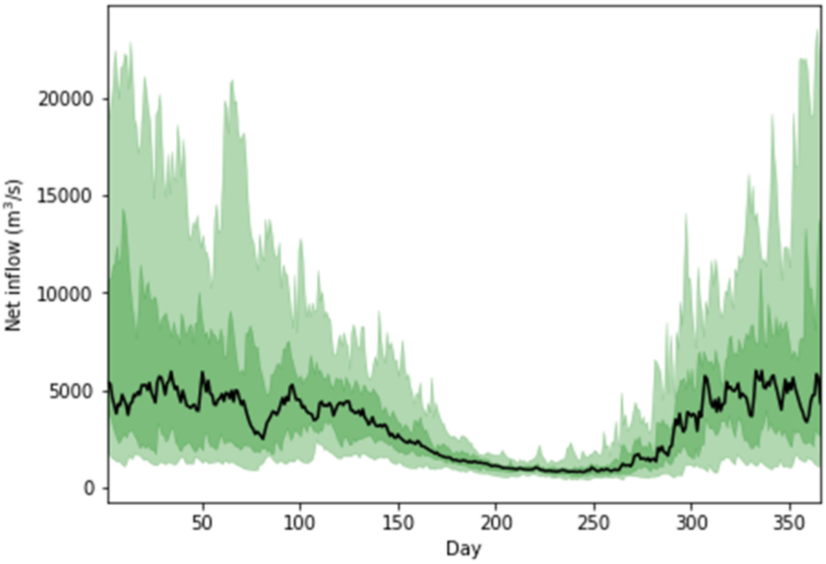


Source: JRC 2017.

4.5 Water inflows

Net water inflow of a specific reservoir can be defined as the gross inflow minus the outflow of upstream reservoir(s). Net inflows are given by the rainfall-runoff hydrological LISFLOOD model [45] and they are assumed to be equal to the total runoff at catchment level. Figure 16 presents the 5th, 25th, 50th, 75th, and 95th percentiles of the historical time series of total net inflows in m^3/s for the Iberian Peninsula for 25 years spanning from 1990 till 2014. The itemised net inflow per catchment can be found in Annex 2.

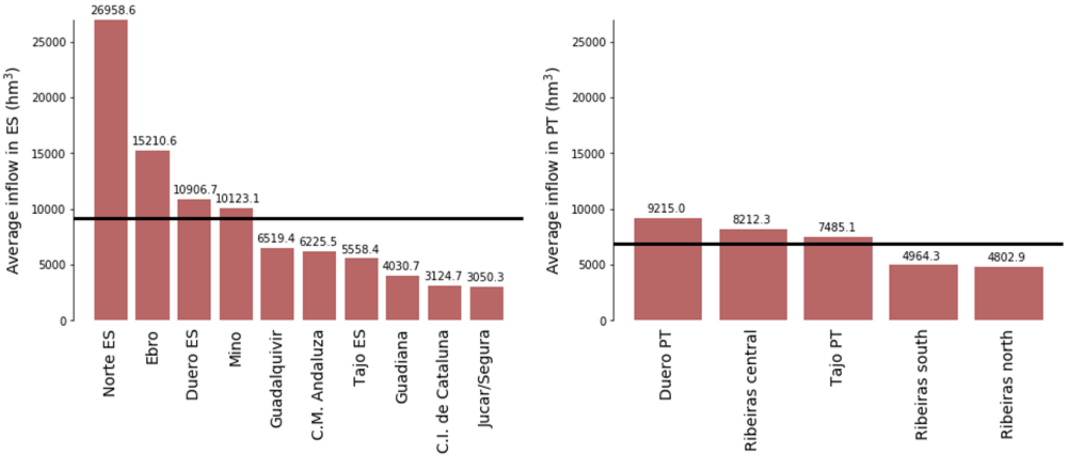
Figure 16. Historical time series of net inflows (m^3/s) for a year. The 5th, 25th, 50th (black line), 75th, and 95th percentiles are presented.



Source: JRC 2017.

Figure 17 provides the average inflow in hm^3 during the 25 years of the daily time series for each catchment in Spain and Portugal. A black line representing the overall average is also depicted in this figure in order to better show the spatial variability of the water runoff in the Iberian Peninsula. As can be seen, there is clear difference between the inflows in the north of Spain (*Norte ES*, *Ebro*, *Duero ES* and *Mino*), which are above the overall average, and the rest of the Spanish territory. Similar differences, although less stressed, can be found in Portugal.

Figure 17. Average inflow per catchment in Spain (ES) and Portugal (PT).



Source: JRC 2017.

4.6 Scenario definition

This work performs a scenario-based analysis of three deterministic and representative scenarios (wet, average and dry historical years). These scenarios are selected from the historical daily time series of water inflows provided by the LISFLOOD model [45], which are presented in section 4.5. The wet, average, and dry historical scenarios correspond to years 1996, 2006, and 2005, respectively, and they are represented in

Figure 18. Their average value during the year, maximum and minimum inflows, as well as the annual inflow are given in Table 7. The total annual inflow for the dry scenario is half of the average scenario whereas the annual inflow for the wet scenario almost doubles the one for the average scenario.

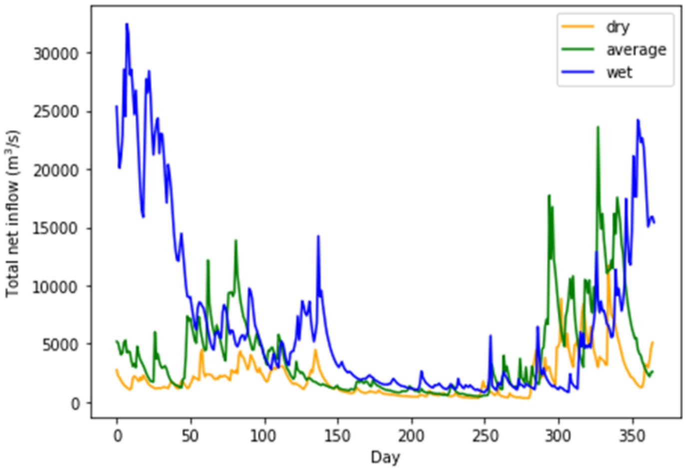
Note that although there are modelling simplifications, a scenario-based analysis could be performed for comparison purposes since those simplifications can be found uniformly across model runs [26].

Table 7. Statistics of net inflows for each scenario.

	Dry - 2005	**Average - 2006**	**Wet - 1996**
Average (m^3/s)	2 052	4 071	6 834
Maximum (m^3/s)	11 722	23 612	32 442
Minimum (m^3/s)	326	483	826
Total (hm^3/s)	0.748	1.486	2.501

Source: JRC 2017.

Figure 18. Historical time series of net inflows (m^3/s) for each scenario.



Source: JRC 2017.

5 Discussion of results

This chapter presents and discusses the results for the Iberian Peninsula case study:

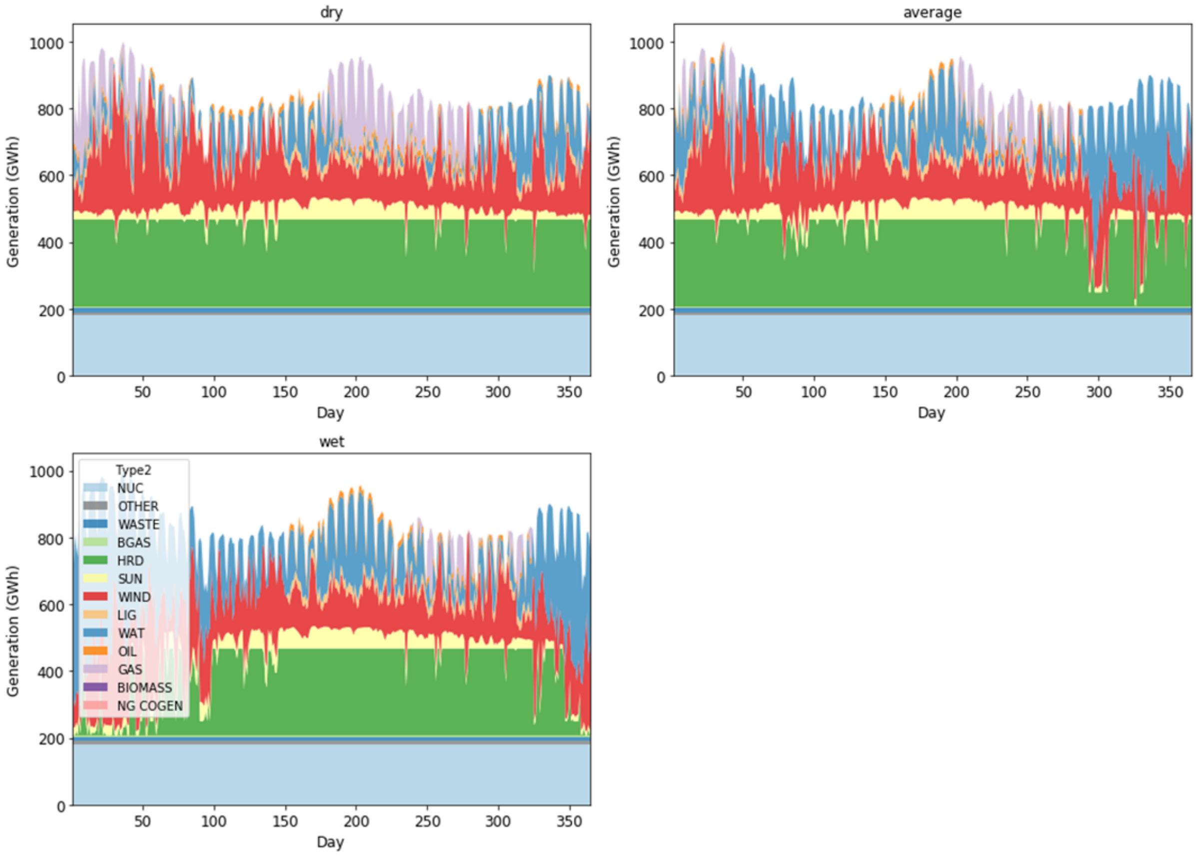
- Section 5.1 analyses results from the Dispa-SET MTHC module.
- Section 5.2 focuses on the results given by the Dispa-SET UCD model.
- Section 5.3 describes results from a vulnerability analysis of two types of cooling-constrained power plants, namely a coal-fired power plant and a nuclear power plant.
- Section 5.4 discusses the effects of cooling-related constraints from a policy perspective.

It should be noted that some water-related inputs such as water inflows or water runoff are simulated and thus may be different from the real ones, which may lead to over- or underestimation of the water needs in practice. However, this work intends to demonstrate the ability of the modelling framework to analyse the water-power nexus of the Iberian Peninsula with high spatial and temporal resolution.

5.1 Outputs from the medium-term operation problem

After running the Dispa-SET MTHC model for the Iberian Peninsula case study, the hydro equivalent units along with the thermal and renewable clusters are optimally dispatched driven by the system-wide generation cost minimisation. Figure 19 shows the daily optimal dispatch for each scenario and fuel type in 2015. It is clear that the hydro units are planned to generate more electricity in the wet scenario than in the average or dry scenarios. On the other hand, the hydro production is mostly replaced by gas units' production in the drier scenarios.

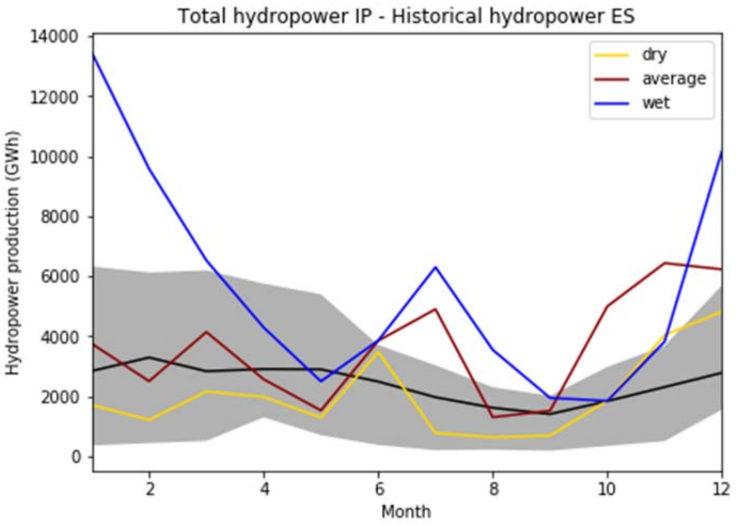
Figure 19. Total energy generation per scenario and fuel type.



Source: JRC 2017.

In order to validate the medium-term outputs, Figure 20 shows the maximum, minimum and average monthly values of historical hydropower production for Spain and the simulated total hydropower production per month for the three scenarios considered in this study. As can be observed in the former figure, the monthly production lies within the historical limits except for the wet scenario because the total water inflows are too high.

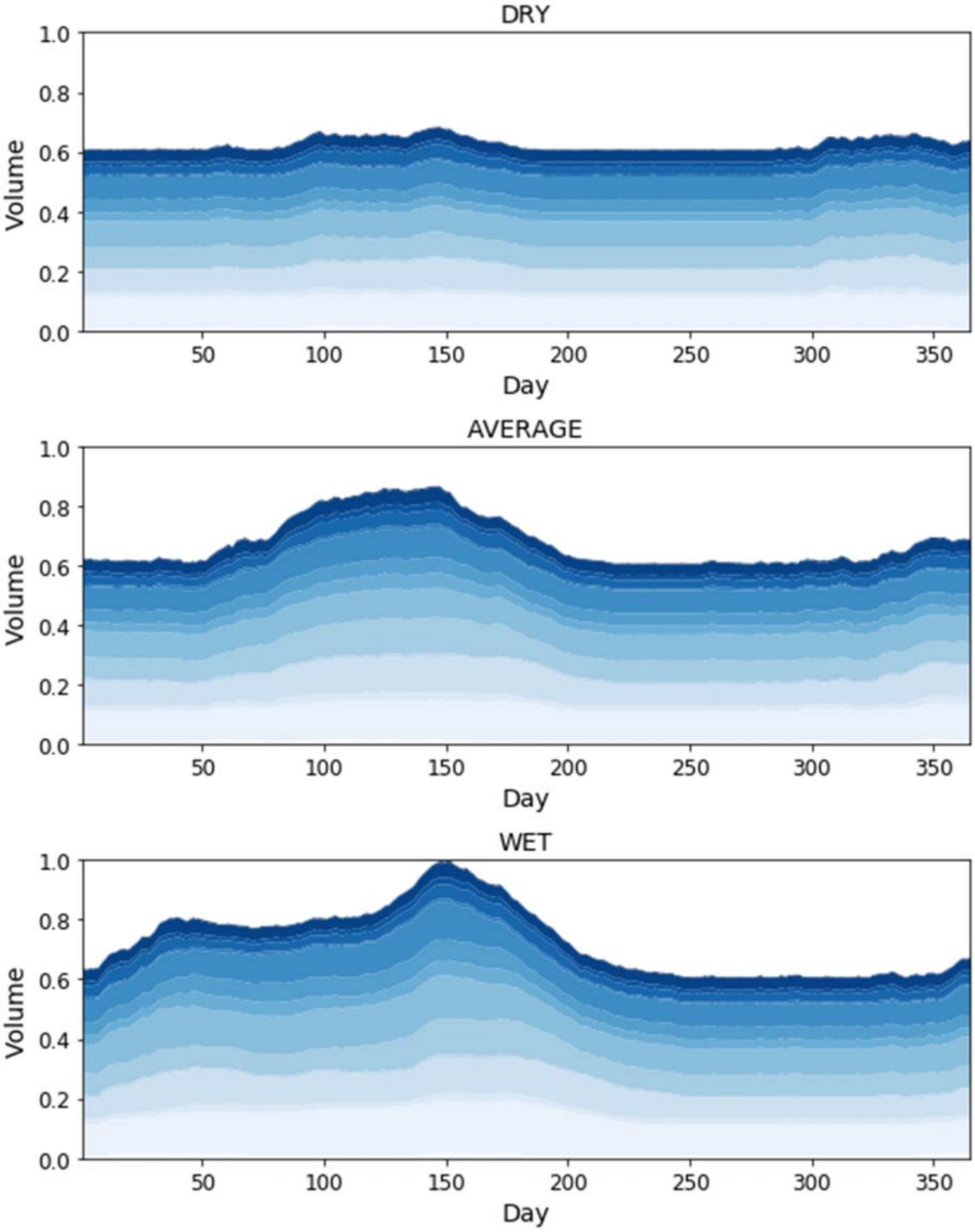
Figure 20. Historical hydropower and total simulated hydropower per month and scenario in Spain (ES).



Source: JRC 2017.

Figure 21 depicts the relative reservoir levels per scenario, which are passed on to Dispa-SET UCD model. Note that there is a minimum volume of 60 % that should be satisfied for all catchments and therefore the reservoir level remains unchanged during the dry scenario. However, in the wet and average scenarios there is an increase of the reservoir levels during spring because of high net inflows at the beginning of 2015. At the end of the year, there are discharges due to hydropower production and the reduction of net inflows during summer.

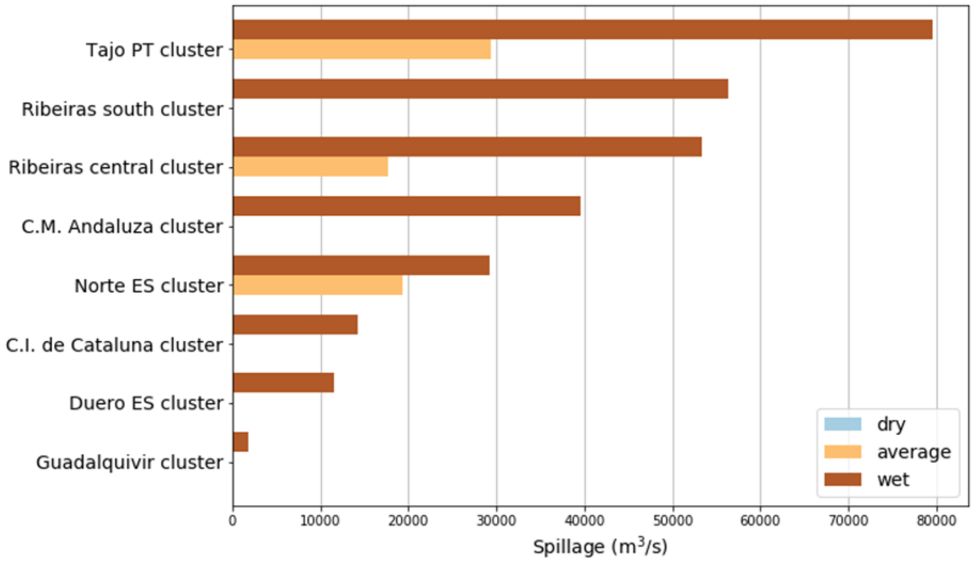
Figure 21. Total reservoir levels per scenario in the Iberian Peninsula.



Source: JRC 2017.

Finally, the total water spillage per catchment and scenario is represented in Figure 22. No water spillage is needed during the dry scenario. In the average scenario, spillage can be found in *Tajo PT*, *Ribeiras Central*, and *Norte ES*, whereas substantial spillage can be found in 8 catchments during the wet scenario. The water spilled by the equivalent reservoirs may be caused because of an excess of net inflows at the beginning of the year in some catchments or the fulfilment of the minimum reservoir level (60 % of the corresponding capacity).

Figure 22. Total water spillage per catchment and scenario.



Source: JRC 2017.

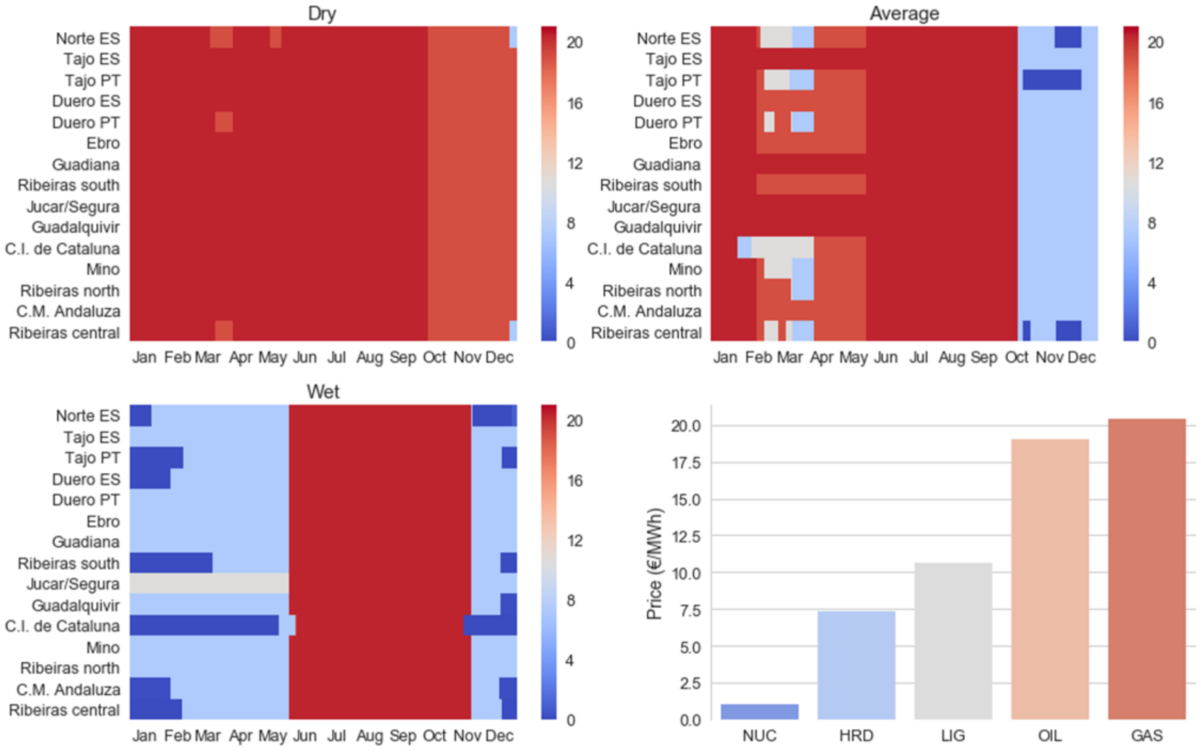
5.1.1 Water value

The water value given as the shadow price of the water balance constraint when minimising the total system-wide generation cost in the mid-term provides valuable information about how to price water. Although we have adopted a primal-based coordination strategy for taking into account mid-term outputs in the short-term operation, i.e. by imposing reservoir levels to the short-term optimisation problem, the water values in the catchments considered for the Iberian Peninsula case study are analysed in Figure 23. Note that the water values correspond to the variable costs assumed for the thermal clusters and their values depend on the marginal unit in each time period.

In Figure 23, the daily water values are represented for each catchment and for each scenario (dark red indicates high water values close to 20 €/MWh whereas dark blue indicates low water values close to 0). In the dry scenario, we can observe that the water values are kept high regardless of the catchment. In the average scenario, there are some periods at the beginning of the year with average water values around 10 €/MWh but only in those catchment located in the north of Spain, wherein the precipitation (and thus the inflows) is usually higher. In summer time, we can also observe high water values for the wet scenario, but there is a clear difference with respect to the winter wherein the water values attain their minimum. It can be seen that the water value is assigned to one of the variable costs associated with the thermal clusters and, as a consequence, its variability is limited to five values. Greater differences may be observed if different variable costs were used throughout the year and more power plants were accounted for (i.e. disaggregation of clusters).

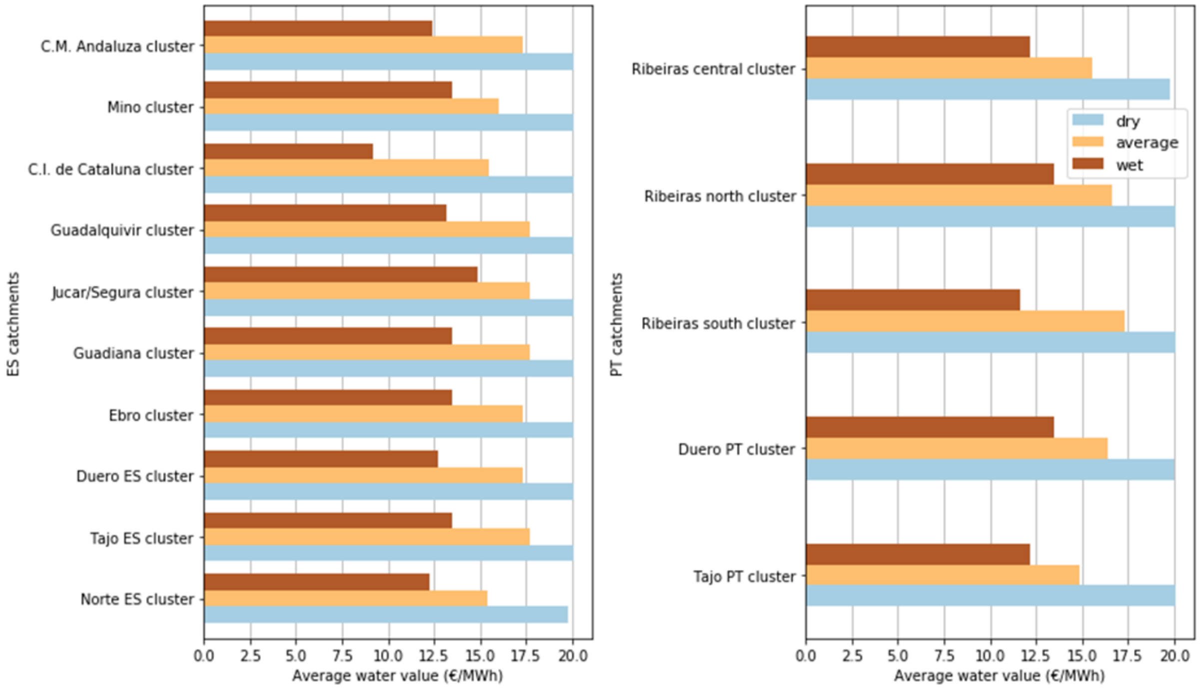
For the sake of completeness, Figure 24 illustrates the average water values throughout the year for each catchment and scenario. There is a clear difference between the water values in the dry, average, and wet scenario, which decrease as the water availability increases. However, the values remain unchanged across catchments due to the reasons given in the last paragraph.

Figure 23. Water value per catchment, period and scenario (upper plots and left lower plot) and fuel prices (right lower plot).



Source: JRC 2017.

Figure 24. Average water value per catchment and scenario.



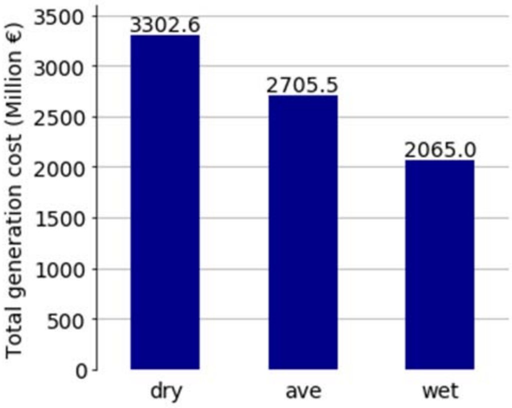
Source: JRC 2017.

5.2 Outputs from the short-term operation problem

5.2.1 Impact of water availability on the power system

Dispa-SET UCD runs three simulations (one for each hydrological scenario) for the year 2015 with a 7-day rolling horizon with an overlap period of one day. The total system-wide generation cost including variable, fixed and penalty costs per scenario is shown in Figure 25. As can be seen, the total system-wide cost is equal to 2 705.5 million € for the average scenario whereas the cost for the dry (wet) scenario increases (decreases) around 22 % (24 %). Therefore, there is a substantial cost difference between the dry and wet scenarios of around 46 %. This is due to differences in the power dispatch, mainly in the hydropower and thermal power production.

Figure 25. Total system-wide generation cost per scenario.

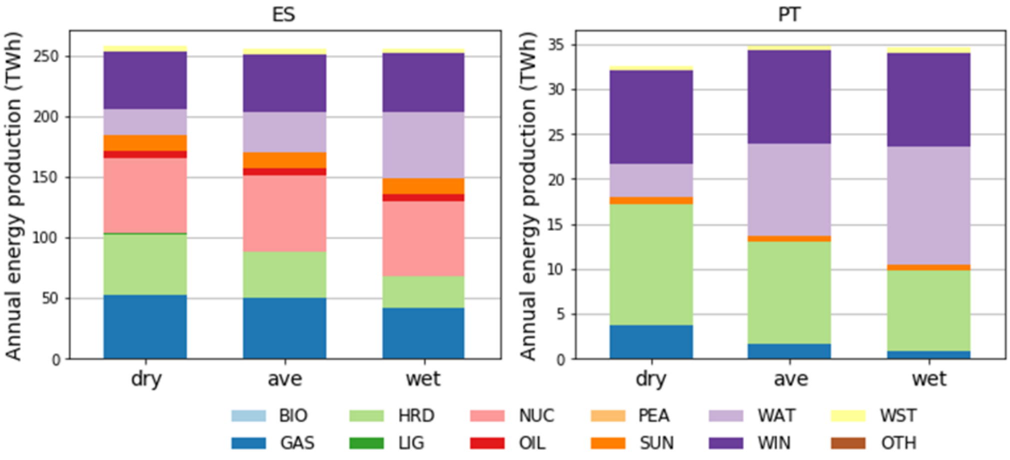


Source: JRC 2017.

The energy production is summarised in Figure 26, Figure 27, and Figure 28. In Figure 26, the annual energy production is represented per country and technology for the three hydrological scenarios. As can be seen, there is a common pattern for the two countries wherein the hydropower production increases and thermal production (gas and coal) decreases when the availability of water is greater. One can observe a small reduction of total annual production in Portugal for the dry scenario, which is compensated by a production increase in Spain. For a better comparison among scenarios in the Iberian Peninsula, Figure 27 shows the major annual energy production variations per fuel type in both dry and wet scenarios over the results provided in the average scenario. The greatest variation can be found for lignite production with an increase of 617 % for the dry scenario and a reduction of 99 % for the wet scenario. Biomass, hard coal, gas and nuclear power production follow the same pattern with smaller variations than lignite production. On the contrary, hydropower production is decreased by 44 % and increased by 55 % for both the dry and wet scenarios, respectively. For the interested reader, Annex 3 includes the power dispatch and unit commitment of all power plants per country and for each scenario.

Figure 26. Annual energy production per fuel type, scenario and country.

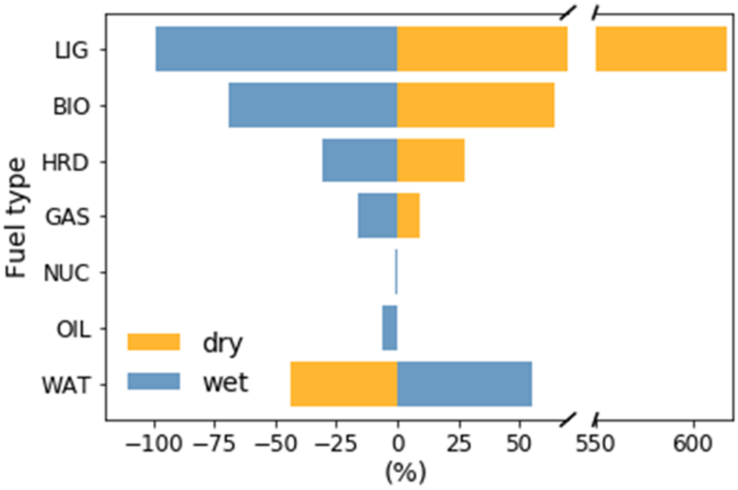
(*Editor's note:* the notation can be found in the list of abbreviations and definitions)



Source: JRC 2017.

Figure 27. Variation of annual energy production per fuel type in scenarios dry and wet over the average scenario.

(*Editor's note:* the notation can be found in the list of abbreviations and definitions)



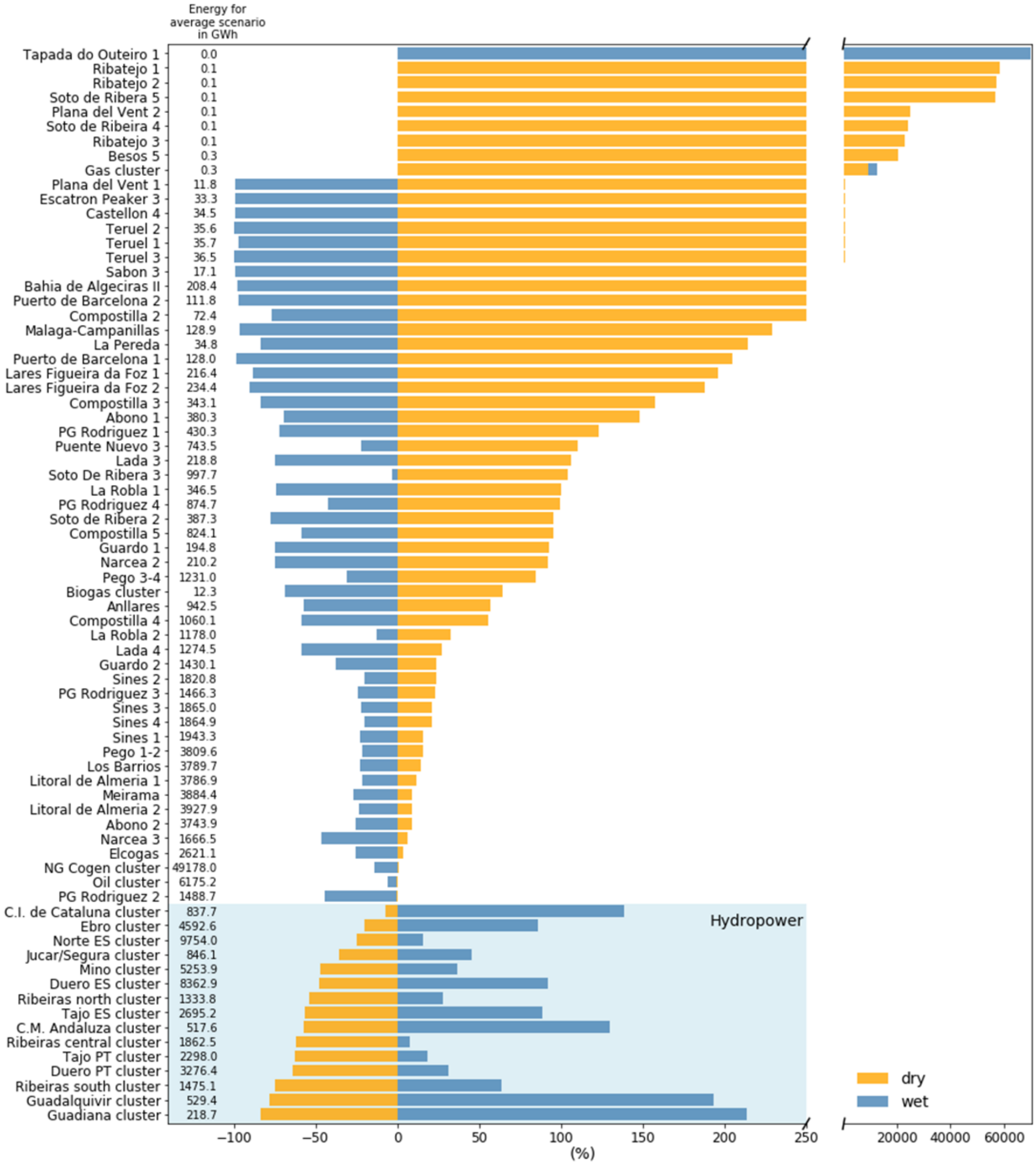
Source: JRC 2017.

Finally, Figure 28 shows the annual energy production variations at power plant level instead of per fuel type for those power plants with a variation greater than 5 % for either wet or dry scenario. At first glance, different patterns can be observed for thermal and hydro power plants, except for *Tapada do Outeiro 1* which also has the greatest variation on energy production for the wet scenario. This is because it was scheduled off for the whole optimisation horizon in the average scenario.

Apart from *Tapada do Outeiro 1*, the greatest variations are observed for the dry scenario in *Ribatejo 1-3*, *Soto de Ribeira 4* and *5*, *Plana del Vent 2*, and *Besos 5* because their annual energy production was below 0.5 GWh for the average scenario; however, these power plants are scheduled off during the year for the wet scenario. The same rationale follows for *Plana del Vent 1*, *Escatron Peaker 3*, *Castellon 4*, *Teruel 1-3*, *Sabon 3*, *Compostilla 2* and *La Pereda*, which have an increase above 200 % for the dry scenario because their annual energy production for the average scenario is very small (i.e. below 100 GWh). The production of these power plants is decreased by 100 % for the wet scenario though. Smaller variations (less than 50 %) in both scenarios can be found for *Sines 1-4*, *PG Rodriguez 3*, *Guardo 2*, *Pego 1-2*, *Litoral de Almeria 1-2*, *Meirama*, *Abono 2*, *Narcea 3*, *Los Barrios*, and *Elcogas* with an annual energy production above 1 TWh for the average scenario.

Regarding the hydropower, the greatest reductions for the dry scenario can be seen in the catchments of *Guadiana*, *Guadalquivir* and *Ribeiras south* with a 75.1, 78.1 and 83.7 % reduction over the results for the average scenario. Also, *Guadiana* and *Guadalquivir* along with *C.M. Andaluza*, which are located at the south of the Iberian Peninsula, show the greatest increases for the wet scenario mainly because their respective annual productions for the average scenario are the smallest of all catchments (below 1 TWh). On the other hand, the catchments *C.I. de Cataluna*, *Ebro* and *Norte ES*, which are located at the north of the Iberian Peninsula show the smallest reductions for the dry scenario (i.e. 7.4, 20.4, and 24.6 % respectively).

Figure 28. Variation of annual energy production per power plant with a variation greater than 5 % in scenarios dry and wet compared to the average scenario.

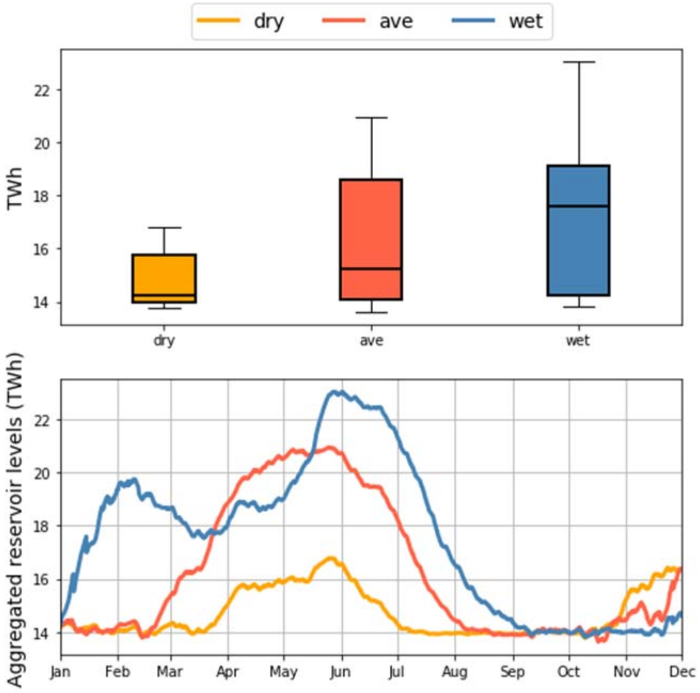


Source: JRC 2017.

5.2.2 Impact of power system operation on water availability

The aggregated hourly reservoir levels in TWh are depicted in the lower plot of Figure 29. The upper plot of such figure shows the corresponding maximum and minimum values, the 25th-percentile, the 75th-percentile, and the median. The pattern of this output is similar for each scenario and maximum peaks are attained in May regardless of the scenario. The maximum reservoir levels are 23.0, 21.0, and 16.8 TWh for the wet, average and dry scenarios respectively. The minimum reservoir levels are reached at the end of the summer and amount to 13.7 TWh. Similar to the Greek case study [57], one can observe a heteroscedastic behaviour of the temporal variability of the reservoir level (difference between the maximum and minimum levels) and standard deviation throughout the year. The temporal variability is equal to 3.0, 7.3, and 9.3 TWh for the dry, average, and wet scenarios, whereas the standard deviation is 0.9, 2.5, and 2.9 TWh.

Figure 29. Aggregated reservoir levels per scenario (lower plot) and statistics (upper plot).



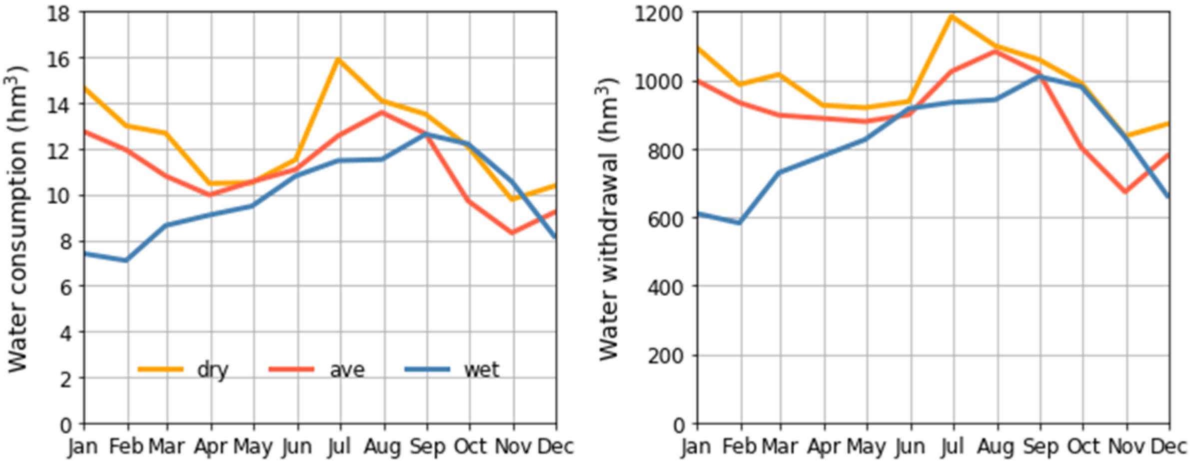
Source: JRC 2017.

The power system operation may substantially impact on water availability for other purposes. Apart from the operation of the hydropower plants, the thermal power plants take fresh water for cooling from different water bodies as reservoirs, lakes, or rivers, and thus affecting the water availability. Next figures are related to the impact of thermal power plants on water scarcity.

The total water withdrawal for cooling thermal power plants is equal to 11 928, 10 882 and 9 807 hm^3 for the dry, average and wet scenarios, respectively. Those quantities account also for the withdrawal of seawater. However, the total water consumption is relatively low for the fleet of thermal power plants in the Iberian Peninsula being 148.6, 133.1 and 119.0 hm^3 for the dry, average and wet scenarios. However, the temporal and spatial disaggregation of those quantities, which are shown in Figure 30 and Figure 31, would be valuable for analysing the water-power nexus.

Figure 30 represents the water consumption (left plot) and withdrawal (right plot) per month. This figure allows us to clearly identify peak withdrawals which would cause water scarcity in the Iberian Peninsula. For instance, we can expectedly observe peak periods around summer (July) for the dry scenario (1 186.3 hm^3), but the peak periods are shifted to August and September when it comes to the average and wet scenarios, respectively (1 083.4 hm^3 and 1 010.4 hm^3). The peak water withdrawals represent roughly 10 % of the annual water withdrawal for all scenarios. On the contrary, the minimum water withdrawals occur in winter: November with 7 % of the annual water withdrawal for the dry scenario, November also with 6.2 % for the average scenario, and February with 5.9 % for the wet scenario. Similar results can be drawn for the water consumption but it is two orders of magnitude less than the water withdrawal.

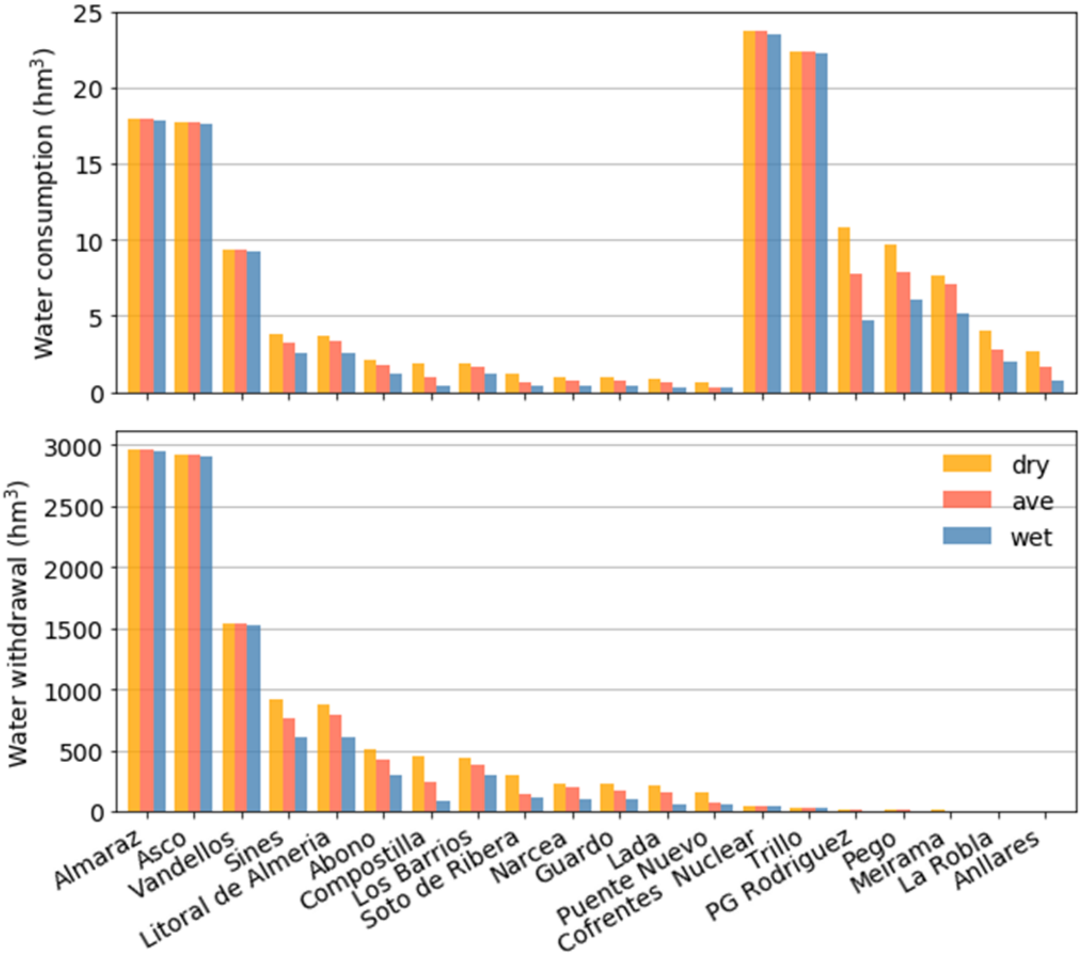
Figure 30. Monthly water consumption and withdrawal per scenario.



Source: JRC 2017.

Spatial disaggregation of water consumption and withdrawal is also quite interesting in order to identify critical power plants which may withdraw too much water for cooling in periods of water scarcity or may not even have enough water for cooling. Figure 31 depicts the yearly water consumed and withdrawn for the power plants with water withdrawal above 100 hm^3 and water consumption above 2 hm^3: *Almaraz*, *Asco*, *Vandellos*, *Sines*, *Litoral de Almeria, Abono, Compostilla, Los Barrios, Soto de Ribera, Narcea, Guardo, Lada, Puente Nuevo* with once-through cooling technologies, and *Cofrentes Nuclear, Trillo, PG Rodriguez, Pego, Meirama, La Robla,* and *Anllares* with natural wet tower cooling technologies. The former group of thermal power plants is characterised by large withdrawals and consumptions, whereas the latter is characterised by larger consumptions and smaller withdrawals than the former. As can be seen, the nuclear power plants *Almaraz, Asco, Cofrentes Nuclear*, and *Trillo* are the greater consumers of water for cooling with annual values above 15 hm^3, according to our simulations and based on average water consumption factors. Note that the real consumptions may differ from these values because of the water consumption factors are estimates from the technical literature per technology [54]. For all of them, the water consumed and withdrawn is greater for the dry scenario than for the average and wet scenario because the hydro power production has been reduced at expense of increasing the thermal power production (see Figure 28 for further details).

Figure 31. Total water consumption and withdrawal for those power plants with water withdrawal above 100 hm^3 and water consumption above 2 hm^3.



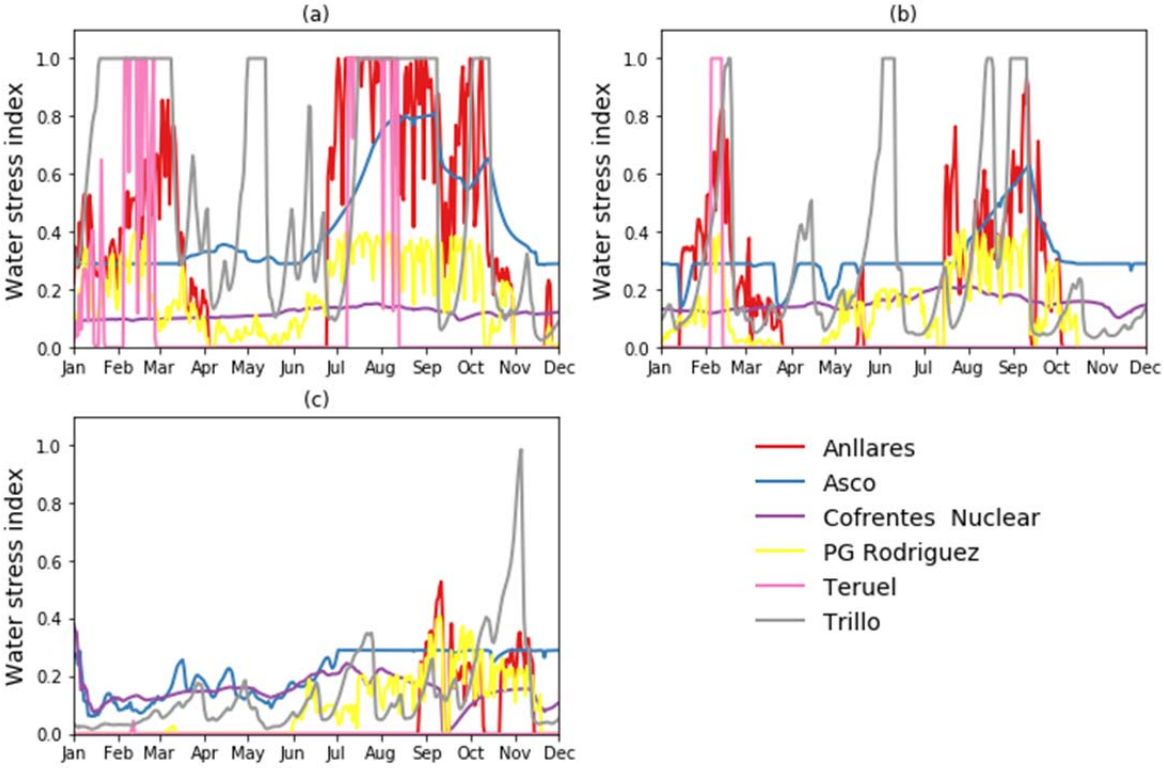
Source: JRC 2017.

Once the water withdrawal is known and assuming that the water runoff can be measured, computed, or estimated anyhow, the water stress index could be computed for each power plant and for each period of time. As defined in [9], the water stress index is the water withdrawn divided by the water runoff. This index varies between 0 if the plant is not stressed at all and 1 if all the water available is used for cooling. The computation of this index would be of highly importance in future power systems in order to maximise the societal welfare or minimise the net costs of both power and water sectors.

In this work the water runoff is given by the rainfall-runoff hydrological LISFLOOD model [45]. Figure 32 shows the water stress index for selected power plants (*Anllares, Asco, Cofrentes Nuclear, PG Rodriguez, Teruel,* and *Trillo*), which may have a water stress index above 0.05 according to our simulations. However, the most critical power plants are *Anllares*, *Teruel*, and *Trillo*, which attain a water stress index equal to 1 more often during the year for the dry scenario. For instance, *Trillo*, *Teruel* and *Anllares* are respectively water stressed for 36 %, 12 %, and 9 % of the year in the dry scenario. Also, we can observe that *Trillo* and *Teruel* achieve a water stress index equal to 1 by 7 % and 2 % of the year in the average scenario, respectively.

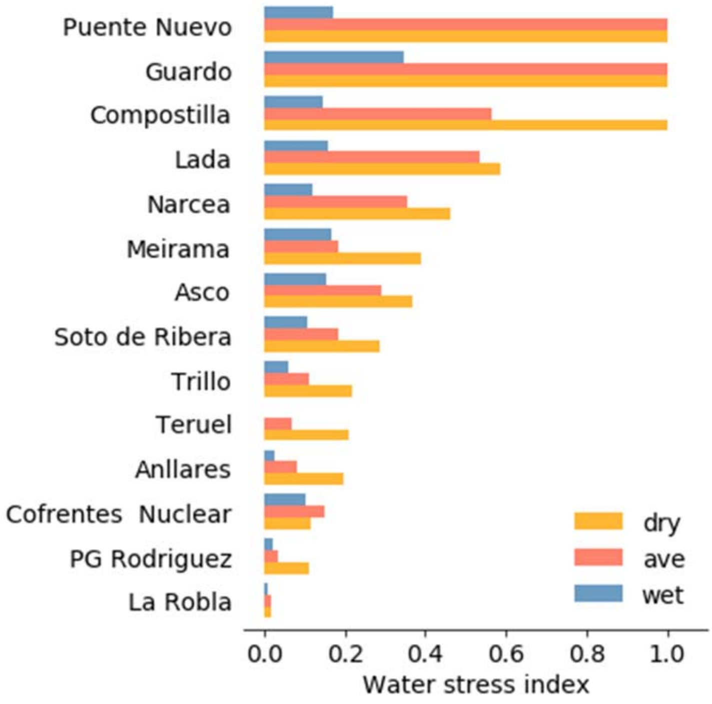
Figure 33 presents an overall water stress index per year and scenario. The overall water stress index increases when the water availability decreases (wet to dry scenario). For instance, *Puente Nuevo, Guardo, Compostilla*, and *Lada* show an annual water stress index above 0.5 for the dry scenario. In addition, the water stress index is below 0.4 for all power plants in Figure 33 for the wet scenario.

Figure 32. Daily water stress index per scenario and catchment. Plots (a), (b) and (c) correspond to dry, average and wet scenarios, respectively.



Source: JRC 2017.

Figure 33. Water stress index per power plant and scenario.



Source: JRC 2017.

5.3 Vulnerability analysis of cooling-constrained power plants

The cooling systems can be categorised in three types: once-through, wet cooling towers and dry cooling. Table 8 summarises some characteristics of each cooling system.

Table 8. Summary of characteristics for cooling technologies used in thermal power plants.

Cooling Type	Water Withdrawal	Water Consumption	Capital Cost	Plant Efficiency	Ecological Impact
Once-Through	Intense	Moderate	Low	Good	Intense
Wet Cooling Towers	Moderate	Intense	Moderate	Good	Moderate
Dry Cooling	None	None	High	Bad	Low

Source: Thesis of A. Martin [58].

For illustration purposes, we run a vulnerability analysis for two types of cooling-constrained power plants, namely a coal-fired power plant with medium-high marginal cost and a nuclear power plant with low marginal cost. To do that, we analyse the effect of cooling-related constraints on water withdrawals ([28]) by changing the corresponding maximum allowable water withdrawn.

5.3.1 A coal-fired power plant case

The water withdrawal constraint imposes maximum allowable water withdrawn per hour in a given thermal power plant. This parameter could be reduced for policy decisions or physical constraints. In order to isolate the effect of this constraint, we set different bounds for the allowable water withdrawn by the *Anllares* power plant. *Anllares* is a coal power plant with an installed capacity of 346.8 MW and a minimum power output of 120.3 MW. By using an average water withdrawal factor (2.2 m^3/MWh), the water withdrawn reaches 770 m^3 at maximum capacity. This amount is modified by different reduction factors ([1.0, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3]) to set up 8 simulations in total.

Figure 34 shows the water stress index of *Anllares* power plant in 2015 for different reduction factors affecting the maximum allowable water withdrawn. We assume that the stressed zone lies within a water stress index of 0.7 and 1.0. Then, we can observe how the water stress index is reduced when the maximum water withdrawn is further restricted. These changes are due to power curtailment and even shutdown of the power plant. As a consequence, the annual production reduction of *Anllares* ranges between 26 % and 100 % compared to the base case. When the maximum water withdrawal is multiplied by a factor of 0.3 (grey line), the water stress index is 0 because the power is constrained below the minimum power output and thus leading to the shutdown of the *Anllares* power plant. On the other hand, this would be the only case with any water stressed day during the year under the assumed stressed zone (above 0.7).

The number of water stressed days for the stressed zone above 0.7 can be easily seen when representing the water stress index duration curve (Figure 35(a)). The number of water stressed days for the base case (factor = 1.0) is 83 and this number decreases as the factor is reduced. Even though the case with a factor of 0.3 is the only one with any water stressed days, significant reductions could be achieved for other cases, *e.g.* 86 % or 80 % for the cases with a reduction factor of 0.4 and 0.5, respectively.

Figure 35(b)-(d) represents the water stress index duration curve and the corresponding number of water stressed days under different stressed zones when policy decisions are more relaxed. We assume respectively stressed zones above 0.8, 0.9 and 1.0. Obviously the number of water stressed days decreases regardless of the case when the policy

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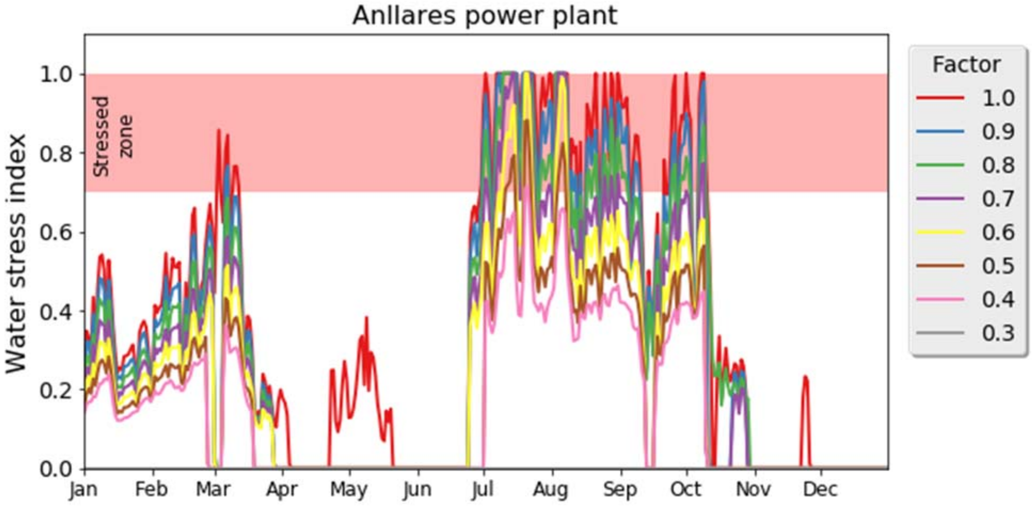
([28]) The constraint is described in [44].

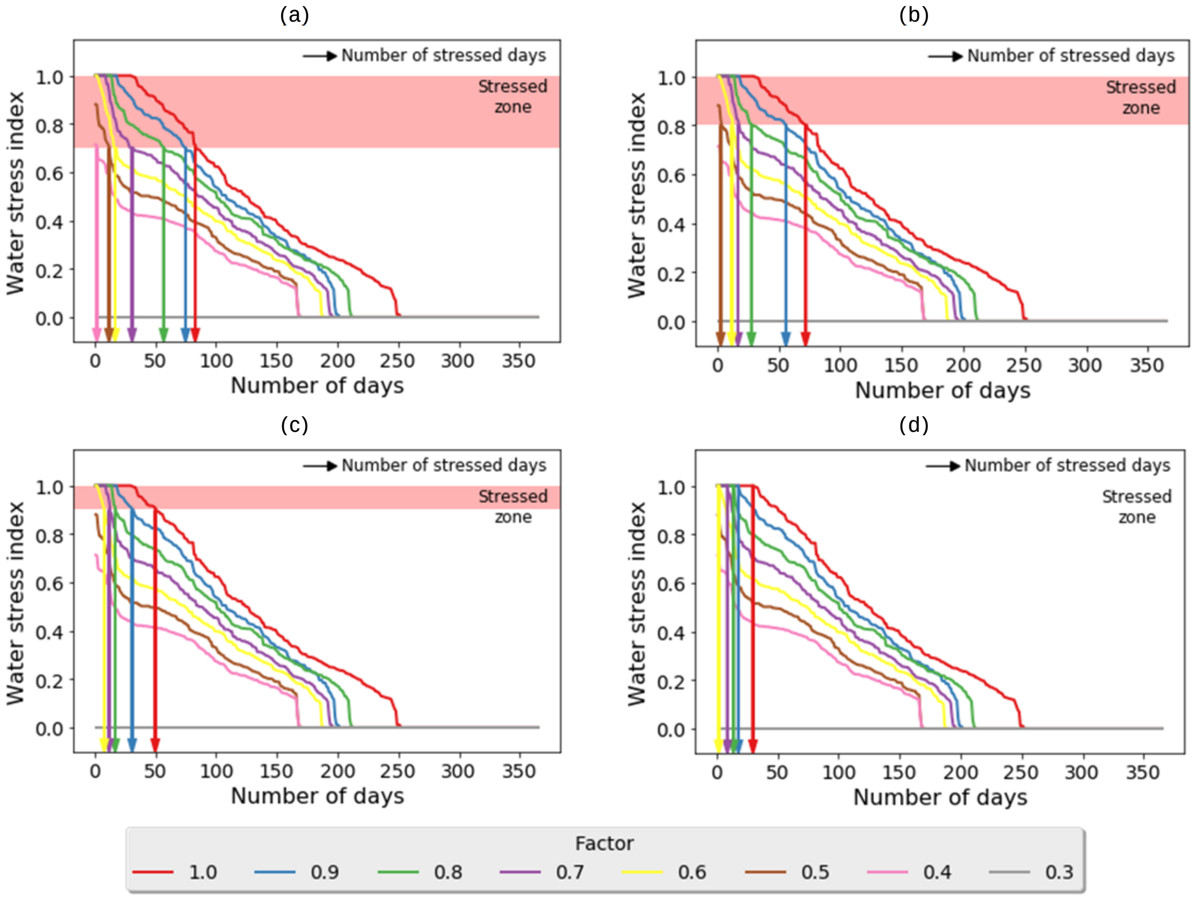
decision is relaxed. For instance, if the stressed zone is simply a water stress index equal to 1 (Figure 35(d)), the cases with reduction factors equal to 0.3, 0.4, and 0.5 would be free of water stressed days, whereas cases with greater factors (0.6 and 0.7) would lead to reductions of 93 % or 70 % compared to the base case.

Figure 34. Water stress index of the *Anllares* power plant for different reduction factors affecting the maximum allowable water withdrawn.



Source: JRC 2017.

Figure 35. Water stress index duration curve of the *Anllares* power plant for different reduction factors affecting the maximum allowable water withdrawn under different stressed zones in the range: (a) [0.7, 1], (b) [0.8, 1], (c) [0.9, 1], and (d) 1.



Source: JRC 2017.

Table 9 shows the number of water stressed days for all cases under different policies regarding the stressed zone. As can be observed, the relaxation of the policy in the unconstrained case (when the lower bound of the stressed zone is increased from 0.7 to 0.8, 0.9 and 1.0) would lead to a reduction of water stressed days by 30 %, 40 %, and 64 %, respectively. If the maximum allowable water withdrawn were affected by a reduction factor of 0.5, the most relaxed policy would result in 0 water stressed days.

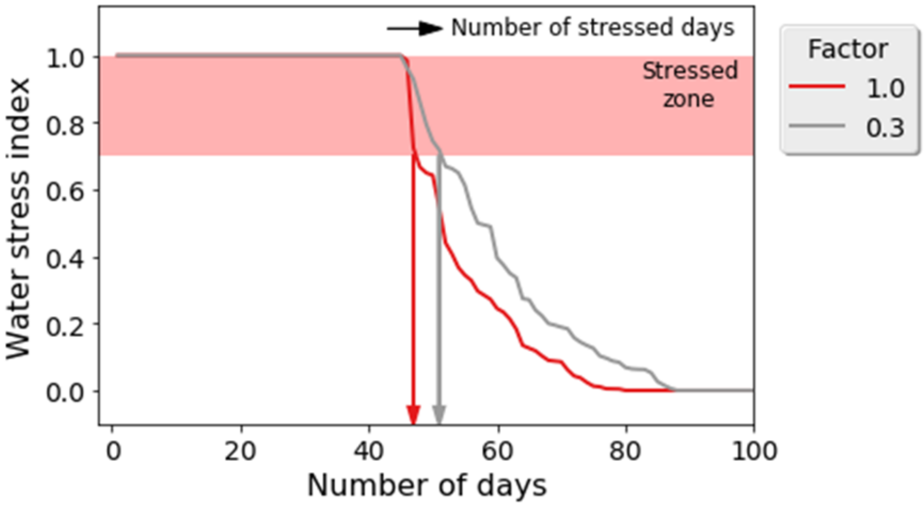
Table 9. Number of water stressed days for different reduction factors affecting the maximum allowable water withdrawn of the *Anllares* power plant under different stressed zones.

Factor	**Stressed zone**			
	[0.7, 1]	**[0.8, 1]**	**[0.9, 1]**	**1**
1.0	83	72	50	30
0.9	75	56	31	18
0.8	57	28	17	14
0.7	31	17	12	9
0.6	17	12	8	2
0.5	12	3	0	0
0.4	2	0	0	0
0.3	0	0	0	0

Source: JRC 2017.

Although the reduction of the water stress index due to the policy constraint is desirable for the *Anllares* power plant, we should raise awareness about the differences in the power dispatch when limiting the maximum water withdrawn. In order to meet the policy constraint, the *Anllares* power plant can curtail power or even shut down, and this power should be supplied by other plant which can cause an increase of its water stress index. For example, Figure 36 shows this case for the *Teruel* power plant. When the maximum water withdrawn for the *Anllares* power plant is further restricted, the number of water stressed days for *Teruel* increases with respect to the unconstrained case (e.g. 9 % for the case with a reduction factor of 0.3). Therefore, a coordinated action (or global policy) should be taken into account in order to apply these constraints and to reduce the overall water stress index.

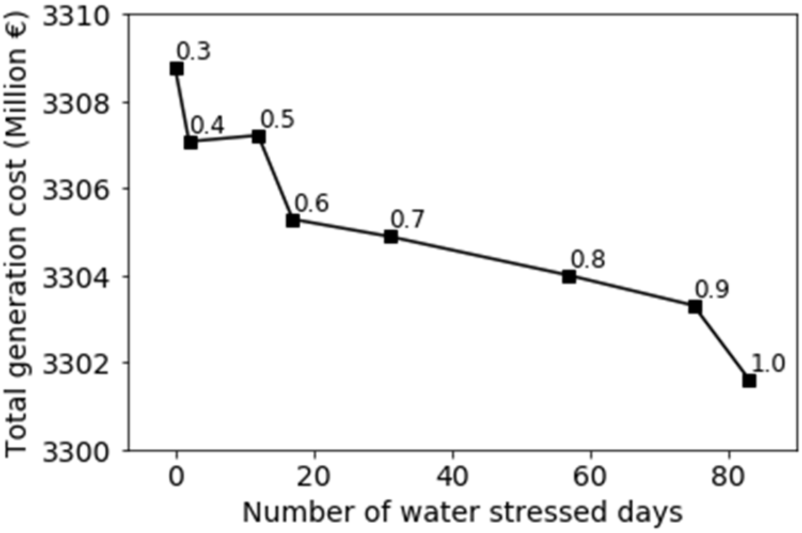
Figure 36. Water stress index duration curve of the *Teruel* power plant when the maximum allowable water withdrawn of the *Anllares* power plant is affected by different reduction factors.



Source: JRC 2017.

Finally, the water withdrawal limitations could have an impact on the total system-wide generation cost. Figure 37 shows the total system-wide generation cost versus the number of water stressed days for the *Anllares* power plant given the stressed zone above 0.7 and for the cases previously mentioned. As can be seen, the generation cost increases when the cooling-related constraint is more stringent. However, since the *Anllares* power plant's capacity is very small compared to the generation fleet's capacity in the Iberian Peninsula, the differences in cost are negligible and ranges between 0.05 % and 0.22 % compared to the unconstrained case for cases with reduction factors of 0.9 and 0.3, respectively. Therefore, improvements in the water stress index could be achieved at expense of negligible generation cost increases.

Figure 37. Total system-wide generation cost versus number of water stressed days for the *Anllares* power plant.



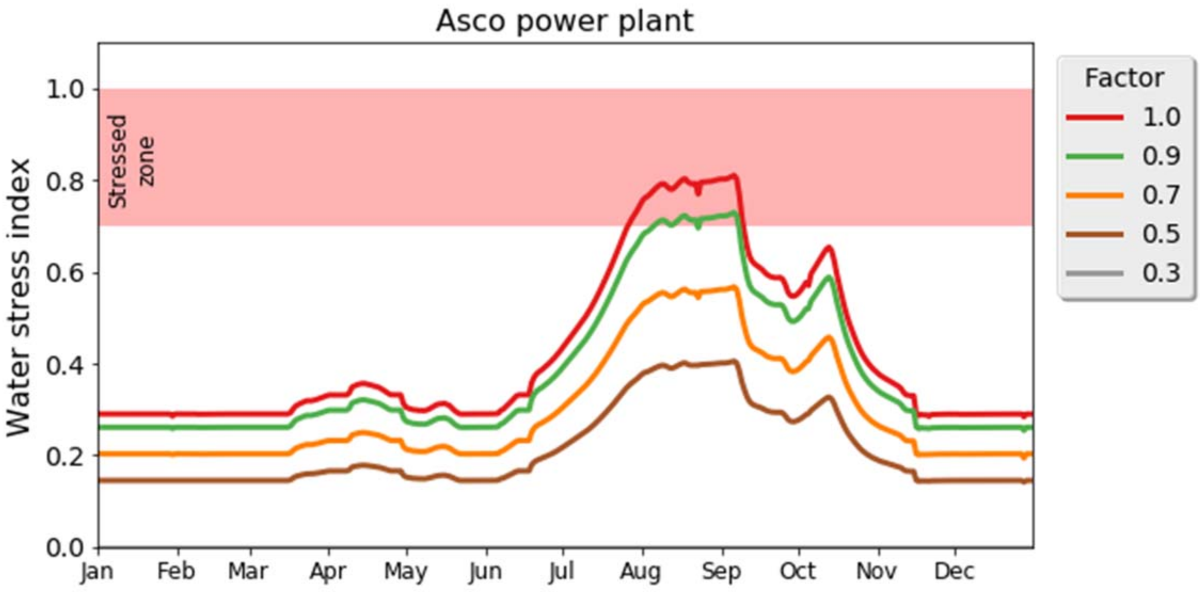
Source: JRC 2017.

5.3.2 A nuclear power plant case

This section analyses the effect of the maximum allowable water withdrawal constraint on a nuclear power plant instead of a coal-fired power plant. This would lead to major operational, and thus economic, consequences due to its reduced fuel cost compared to a coal-fired power plant. The selected nuclear power plants are *Asco 1* and *Asco 2* with a total installed capacity of 2 GW and a minimum power output equal to 800 MW. The total water withdrawn is 0.3 hm^3 at maximum capacity. As similarly done with *Anllares*, the maximum allowable water withdrawn throughout the year is equal to the water withdrawn at maximum capacity times different reduction factors ([1.0, 0.9, 0.7, 0.5, 0.3]).

Figure 38 shows the water stress index of the *Asco* power plant in 2015 for different reduction factors affecting the maximum allowable water withdrawn. We assume that the water restriction is due to policy decisions and that the stressed zone with a water stress index above 0.7 should be avoided. When the water withdrawn is further restricted, we can observe how the water stress index is reduced below the stressed zone due to power curtailment and even shutdown of the power plant.

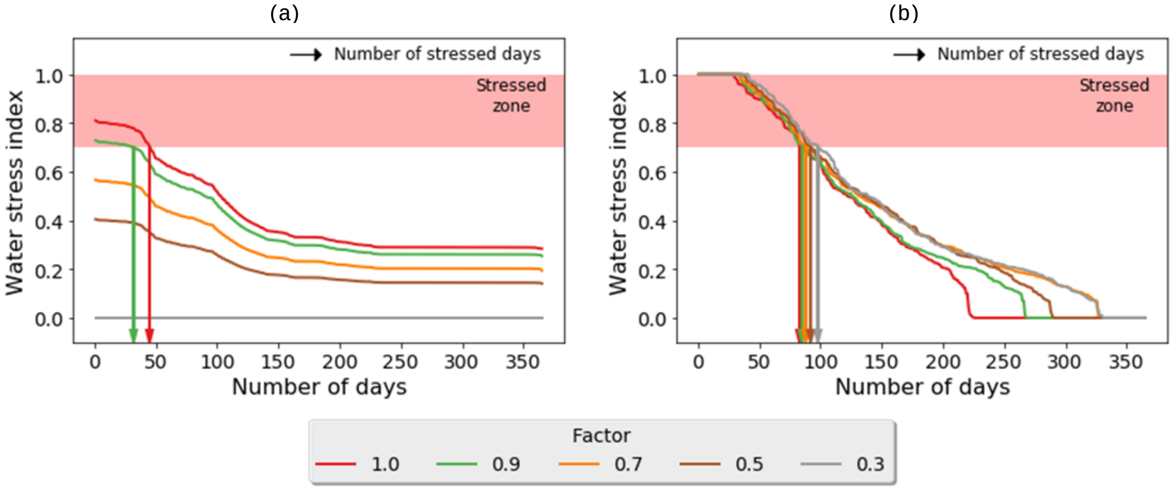
Figure 38. Water stress index of the *Asco* power plant for different reduction factors affecting the maximum allowable water withdrawn.



Source: JRC 2017.

Figure 39(a) represents the water stress index duration curve of *Asco*. We can see that the number of water stressed days for the unconstrained or base case (factor = 1.0) is 45 and this number is decreased to 32 days for the case with a reduction factor equal to 0.9. For the rest of cases, the power plant meets the policy criterion and the water stress index is always below 0.7 for all year long. However, we can observe an increase in the number of water stressed days for *Anllares*. In the case with a reduction factor of 0.7, the number of water stressed days for the *Anllares* power plant increases by 6 %. In the worst-case scenario, if the *Asco* power plant was scheduled off for the whole year, then the number of days for the *Anllares* power plant would increase by 18 %.

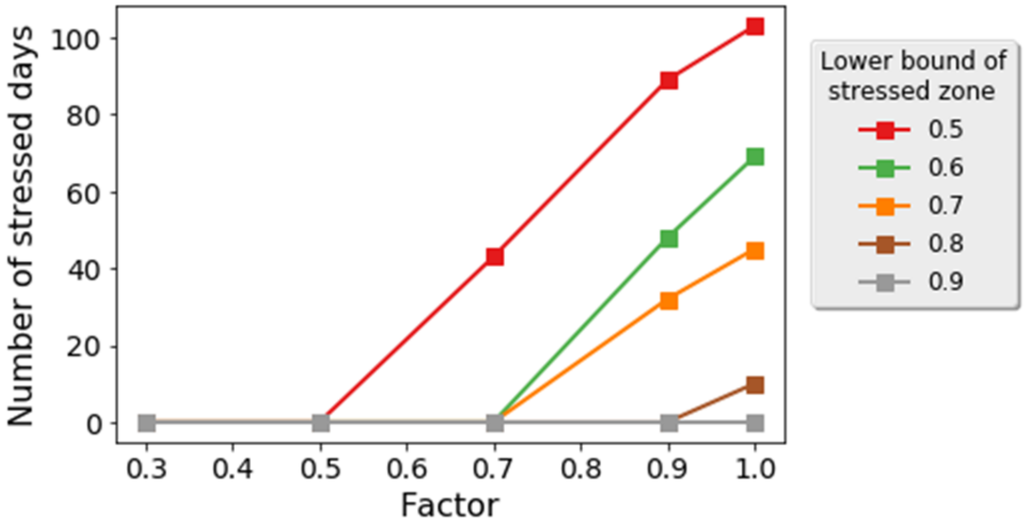
Figure 39. Water stress index duration curve of the *Asco* power plant (a) and the *Anllares* power plant (b) for different reduction factors affecting the maximum allowable water withdrawn.



Source: JRC 2017.

Different policies could be adopted by varying the stressed zone. Let us consider five different policies with lower bounds of the stressed zone ranging from 0.5 to 0.9. Figure 40 illustrates the number of water stressed days for different factors affecting the maximum allowable water withdrawn of the *Asco* power plant under the policies mentioned above. As can be seen, if a relaxed policy were considered, the power plant would always meet the water stress index requirements (always below 0.9). On the other hand, when the policy is further restricted, the number of water stressed days would increase for each of the cases. For instance, assuming the most restricted policy with a lower bound equal to 0.5, the number of days is increased to 103, 89, and 43 for the cases with reduction factors of 1.0, 0.9, and 0.7, respectively. For that policy, the power plant would be always below 0.5 when the water withdrawal is at least reduced by 50%.

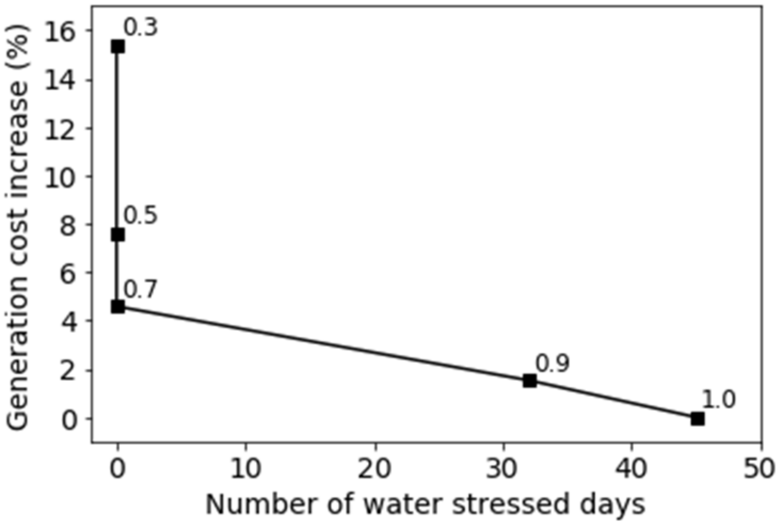
Figure 40. Number of water stressed days for different reduction factors affecting the maximum allowable water withdrawn of the *Asco* power plant under different stressed zones.



Source: JRC 2017.

Finally, there is a major impact on the system-wide generation cost when the *Asco* power plant is affected by cooling-related constraints compared to the *Anllares* case, as can be seen in Figure 41. The generation cost would increase by 4.6 % (compared to the unconstrained case) to reach a water-stress-free state for the *Asco* power plant (considering a water stressed zone above 0.7). In the worst-case scenario, the total system-wide cost would be slightly greater than 15 % (compared to the unconstrained case) if the *Asco* were shut down for the whole year.

Figure 41. Total system-wide generation cost increase versus number of water stressed days for the *Asco* power plant.



Source: JRC 2017.

5.4 Effect of cooling-related constraints: A policy perspective

This section is devoted to analyse the effect of cooling-related constraints on thermal power plants from a policy perspective. In order to keep the water stress index outside the required stressed zone while minimising the system-wide generation cost, the water stress index could be endogenously taken into account in the water-related unit commitment model. To do that, we impose that the water withdrawn (computed as the water withdrawal factor multiplied by the power output) divided by the total available runoff should be less than a pre-specified water stress index per thermal power plant and time period (29).

As can be seen in Figure 32(a), the *Cofrentes Nuclear* and *PG Rodriguez* power plants are not water-stressed in the dry scenario, however the number of water-stressed days (assuming a stressed zone above 0.7) is equal to 45, 46, 83, and 145 days for the *Asco*, *Teruel*, *Anllares*, and *Trillo* power plants. Therefore, Figure 42 represents the water stress index for those power plants and for different cases:

- 'Base case': unconstrained case for the dry scenario.
- '*Anllares* case': the water stress index limit is set to 0.7 for the *Anllares* power plant only during the optimisation horizon.
- '*Asco* case': the water stress index limit is set to 0.7 for the *Asco* power plant only during the optimisation horizon.
- '*Teruel* case': the water stress index limit is set to 0.7 for the *Teruel* power plant only during the optimisation horizon.
- '*Trillo* case': the water stress index limit is set to 0.7 for the *Trillo* power plant only during the optimisation horizon.
- 'All case': the water stress index limit is set to 0.7 for all of them, the *Anllares*, *Asco*, *Teruel*, and *Trillo* power plants.

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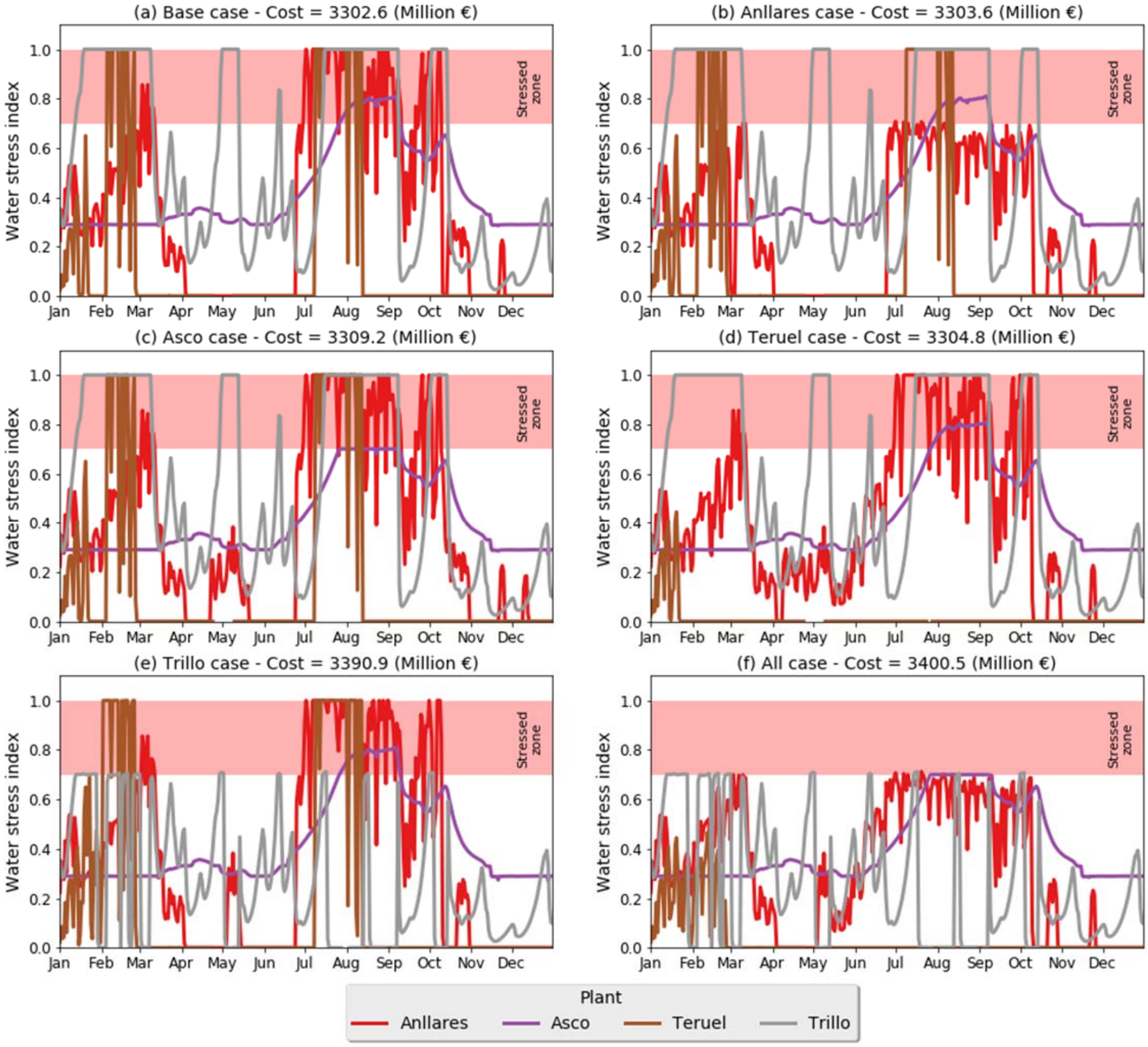
(29) The constraint is described in [44].

Hence, '*Anllares* case', '*Asco* case', '*Teruel* case', and '*Trillo* case' represent individual strategies in order to keep the water stress index below a pre-specified threshold and 'All case' represents a global policy which leads to an optimal strategy. Moreover, the system-wide generation cost is provided for each case in the title of the corresponding subplot.

As can be observed, the power plants are able to operate while satisfying the stressed zone above 0.7 at expense of a power production reduction in certain periods and thus increasing the system-wide generation cost. Individual policies or strategies lead to smaller generation cost increases than a coordinated strategy (or global policy); however the remaining power plants in individual cases still work under water-constrained periods.

Figure 42. Water stress index for the *Anllares, Asco, Teruel* and *Trillo* power plants and for different cases: (a) 'Base case' (unconstrained); (b) '*Anllares* case', (c) '*Asco* case', (d) '*Teruel* case', (e) '*Trillo* case' (individual strategy); and (f) 'All case' (coordinated strategy).

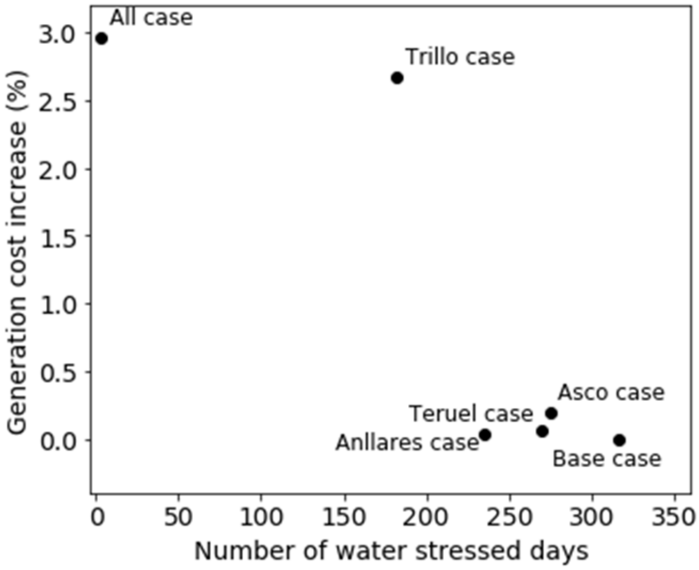


Source: JRC 2017.

For the sake of completeness, Figure 43 shows the generation cost in percent over the 'Base case' versus the total number of water stressed days for the four selected power plants. The water stressed days are those in which the water stress index is above

0.7 ([30]). Individual strategies for *Asco*, *Teruel* and *Anllares* lead to generation cost increases below 0.2 %. As compared to the constraint on water withdrawals for the *Asco* power plant, the water stress index is kept within limits by slightly increasing the generation cost. Therefore, implementing a water stress index constraint would be more cost-effective than a constraint on the maximum allowable water withdrawal. However, this would require the previous knowledge of the water runoff or, at least, a good estimation of the water runoff during the power scheduling. On the other hand, the *Trillo* power plant meets the water stressed zone by increasing the system-wide generation cost by 2.7 % since it shuts down during some periods. Finally, when the four power plants are required to collectively satisfy a certain water stress index limit, the generation cost is then increased by 3 %. In Figure 44, we can observe that the generation cost duration curve for the 'All case' is slightly above than the one for the 'Base case'.

Figure 43. Total system-wide generation cost increase versus number of water stressed days for all cases.



Source: JRC 2017.

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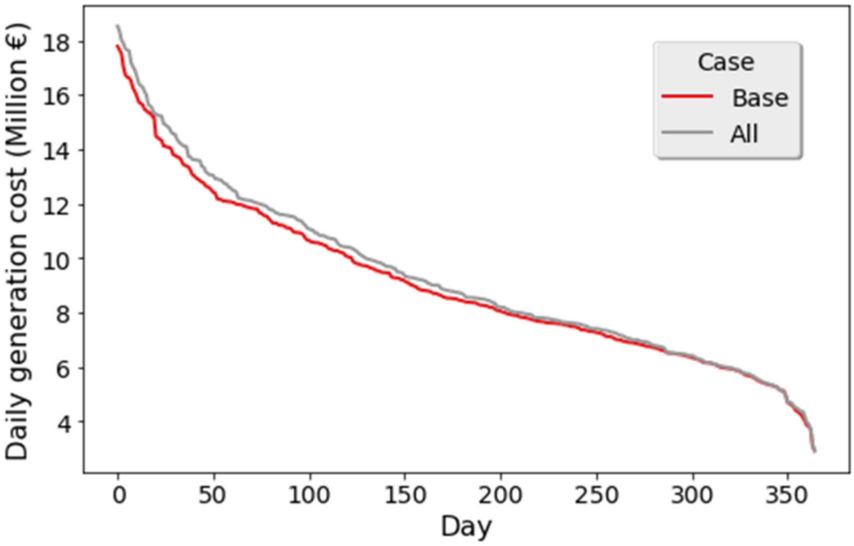
[30] There may be some days with a water stress index slightly above 0.7 since the water stress index constraint is imposed hourly. As a consequence, it may lead to some mismatches in the daily computation of the water stress index and may underestimate the system-wide generation cost.

Figure 44. Daily generation cost duration curve for the ‘Base case’ and ‘All case’.



Source: JRC 2017.

Figure 45 shows the annual energy production variation of the ‘All case’ at power plant level for those power plants with a variation greater than 5 % over the ‘Base case’. The power curtailed to meet water-related constraints causes the increase in energy production by *Sagunto 2, Sagunto 1, Castejon 2,* and *PG Rodriguez 5* above 400 % over the respective productions in the ‘Base case’. However, there are more than 30 power plants increasing their production to compensate alterations in the power dispatch. We can observe also power reductions in other plants apart from *Trillo, Asco, Teruel* and *Anllares*. The reasons may be twofold: 1) changes in order to meet all technical constraints at minimum cost and 2) changes because other near-optimal solutions may be attained (31). Variations of annual energy production for the remaining cases are shown in Annex 4.

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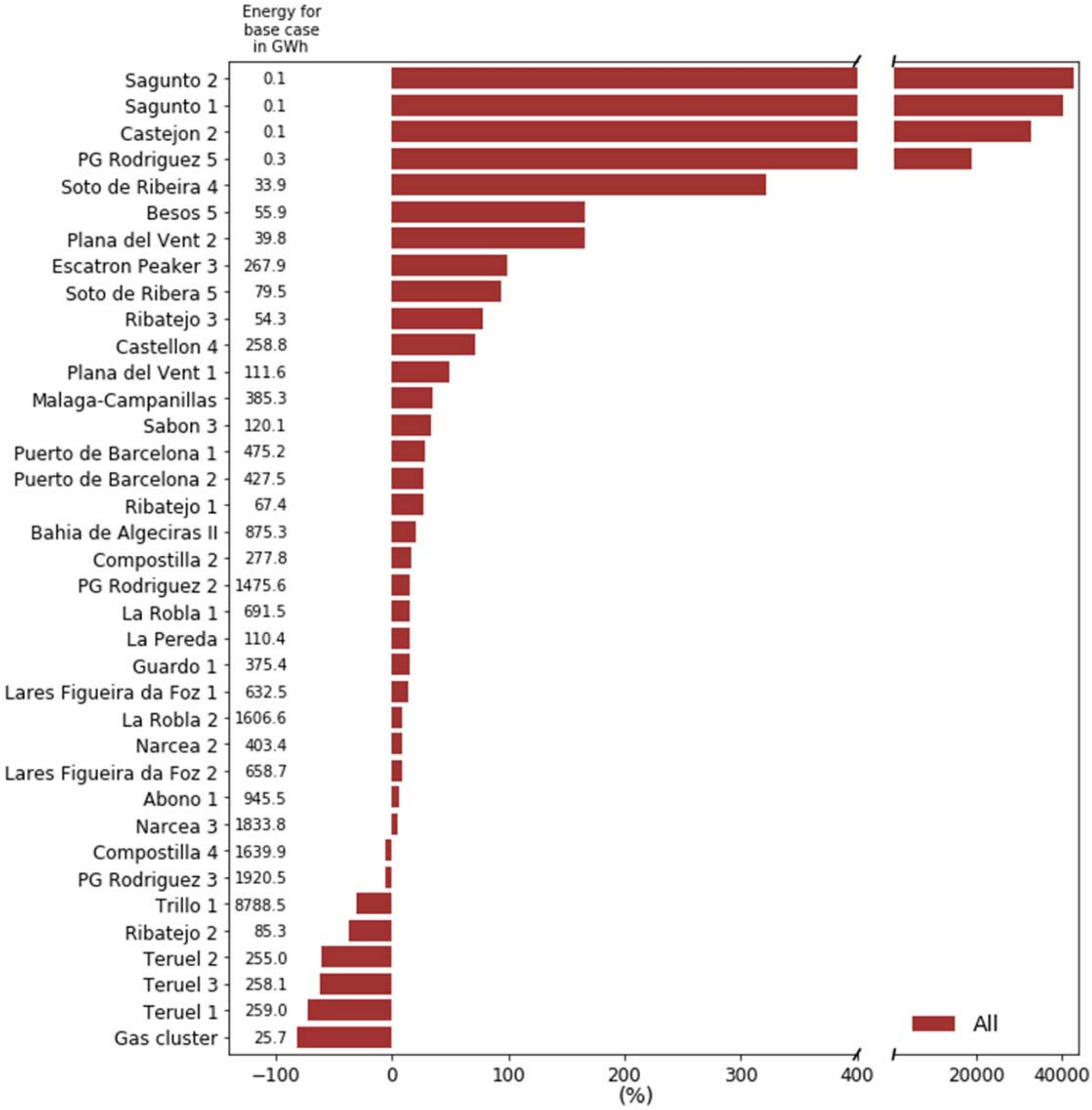
(31) Note that an optimality gap of 0.1 % is assumed for the simulations.

Figure 45. Variation of annual energy production per power plant with a variation greater than 5 % for the 'All case' compared to the 'Base case'.



Source: JRC 2017.

6 Conclusions

The water-power framework adopted within the WATERFLEX project has been applied to the Iberian Peninsula. This report provides a sound and detailed analysis of the interactions between the water and power systems for three historical hydrological scenarios (dry, average and wet).

This report also performs assessments of the implications of water availability on power system economics and operations and the consequences of power system operations on water availability. Moreover, a vulnerability analysis of cooling-related constraints on maximum allowable water withdrawal has been carried out for two different power plants: a coal-fired power plant with a high marginal cost and moderate installed capacity, and a nuclear power plant with a low marginal cost and high installed capacity. In addition, we perform analyses for a constraint that endogenously takes into account the water stress index and discuss the results from a policy perspective.

It should be noted that some water-related inputs such as water inflows or water runoff are simulated and thus may be different from the real ones, which may lead to over- or underestimation of the water needs in practice. However, this work intends to demonstrate the ability of the modelling framework to analyse the water-power nexus of the Iberian Peninsula with high spatial and temporal resolution.

The following conclusions are drawn from this study:

- Water pricing will be an issue in forthcoming water-constrained power systems and thus we provide an insight of the water value per catchment with a daily temporal resolution.
- Water shortages (low flows) or policy decisions due to water restrictions could modify the available maximum capacity of certain water-stressed power plants, thus leading to system-wide generation cost increases or even shifting the water stress index to other power plants. Therefore, a global policy (or coordinated strategy) should be taken into account to keep the water stress index of all thermal power plants within limits imposed due to policy restrictions or physical limitations.
- Water stress index could be endogenously taken into account in the unit commitment model providing less costly dispatch and commitment solutions while satisfying certain water stressed limits.
- A global policy to keep the water stress index within adequate (policy or physical) levels lead to generation cost increases.

However, further work is needed to better analyse such complex conundrum between the water and power, and thus providing informed decisions for policy-makers. The following avenues of work are required:

- Further disaggregation of hydro power plants within a catchment which would provide more accurate water values per hydro power plant. In addition, this would allow for a better representation of pumped-hydro units.
- Analysis of future climate scenarios wherein the consequences of water scarcity would be exacerbated and the vulnerability of thermal power plants would be higher.
- Joint optimization of irrigation and power system models driven by social welfare maximisation (or net cost minimisation).

Finally, the assessment of the water-power nexus will be expanded to other strategic regions such as the Western Balkans, European Union, or some regions of Africa.

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List of abbreviations and definitions

APA	The Portuguese Environment Agency (*Agência Portuguesa do Ambiente*)
BGAS	Biogas
BIO	Biomass
COMC	Combined cycle
C.I.	Cuencas Internas
C.M.	Cuenca Mediterránea
Dispa-SET MTHC	Dispa-SET Medium-Term Hydrothermal Coordination
Dispa-SET UCD	Dispa-SET Unit Commitment and Dispatch
DOE	United States Department of Energy
EDP	Energias de Portugal: a Europe's major electricity operator
ENTSO-E	European Network of Transmission System Operators for Electricity
ES	Spain
GTUR	Gas turbine
HDAM	Conventional hydro dam
HRD	Hard coal
IASS	Institute for Advanced Sustainability Studies
ICOLD	International Commission on Large Dams
IEA	International Energy Agency
IMF	International Monetary Fund
INAG	The Water Institute (*INstituto da ÁGua*)
IP	Iberian Peninsula
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LIG	Lignite
MAPAMA	The Ministry of Agriculture and Fisheries, Food and Environment (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente*)
MENA	Middle East North Africa
NG COGEN	Natural gas cogeneration
NUC	Nuclear
OTH	Other
PEA	Peat Moss
PHOT	Solar photovoltaic
PT	Portugal
RoH	Rest of hydro
SNIRH	The National Water Resources Information System SNIRH (*O Sistema Nacional de Informação de Recursos Hídricos*)

STUR	Steam turbine
US	United States
SUN	Solar energy
WAT	Hydro energy
WEO	World Energy Outlook
WIND	Wind energy
WST	Waste
WTON	Onshore wind turbine

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Annexes

Annex 1. Techno-economic features of the generating units

This annex comprises the techno-economic features of the generating units considered for the Iberian Peninsula case study when running simulations in the Dispa-SET UCD model. Table 10 shows the country where each unit belong to, its technology and fuel type, the corresponding capacity, the minimum generation level in percentage with respect to the capacity and the efficiency [13], [14], [59]. Table 11 includes the minimum up and down times, ramp up and down rates, start-up costs, minimum efficiencies, start-up times, and CO_2 intensity [59]. Finally, Table 12 collects the withdrawal factor of each power plant based on the average factors provided in [54].

Table 10. Techno-economic features of the generating units considered in the Iberian Peninsula for the Dispa-SET UCD model.

(*Editor's note:* the notation can be found in the list of abbreviations and definitions)

Unit	Zone	Technology	Fuel	Capacity (MW)	Minimum power output (%)	Efficiency (%)
Abono 1	ES	STUR	HRD	341.7	0.35	0.336
Abono 2	ES	STUR	HRD	535.8	0.35	0.371
Aceca CC3	ES	COMC	GAS	386	0.38	0.565
Aceca CC4	ES	COMC	GAS	372.6	0.38	0.565
Almaraz 1	ES	STUR	NUC	1 011.3	0.4	0.314
Almaraz 2	ES	STUR	NUC	1 005.8	0.4	0.314
Amorebieta	ES	COMC	GAS	786.4	0.38	0.565
Anllares	ES	STUR	HRD	346.8	0.35	0.347
Arcos de la Frontera 3	ES	COMC	GAS	822.8	0.38	0.565
Arcos de la Frontera 1	ES	COMC	GAS	389.2	0.38	0.565
Arcos de la Frontera 2	ES	COMC	GAS	373.2	0.38	0.565
Arrubal 1	ES	COMC	GAS	394.6	0.38	0.565
Arrubal 2	ES	COMC	GAS	390	0.38	0.565
PG Rodriguez 1	ES	STUR	HRD	350.9	0.35	0.336
PG Rodriguez 2	ES	STUR	HRD	351	0.35	0.347
PG Rodriguez 3	ES	STUR	HRD	350.2	0.35	0.347
PG Rodriguez 4	ES	STUR	HRD	350.8	0.35	0.347
PG Rodriguez 5	ES	COMC	GAS	855.6	0.325	0.579
Asco 1	ES	STUR	NUC	995.8	0.4	0.314
Asco 2	ES	STUR	NUC	991.7	0.4	0.314
Bahia de Algeciras II	ES	COMC	GAS	820.5	0.325	0.59
Bahia de Bizkaia	ES	COMC	GAS	785.3	0.38	0.565
Besos 3	ES	COMC	GAS	411.9	0.38	0.565
Besos 4	ES	COMC	GAS	399.7	0.38	0.565
Besos 5	ES	COMC	GAS	859	0.325	0.579
Castejon 3	ES	COMC	GAS	418.4	0.38	0.565
Castejon 1	ES	COMC	GAS	424.9	0.38	0.565
Castejon 2	ES	COMC	GAS	378.9	0.325	0.579
Castelnou 3	ES	COMC	GAS	782	0.38	0.565
Castellon 4	ES	COMC	GAS	839.3	0.325	0.579
Castelnou	ES	COMC	GAS	790.6	0.38	0.565

Unit	Zone	Technology	Fuel	Capacity (MW)	Minimum power output (%)	Efficiency (%)
Cofrentes Nuclear	ES	STUR	NUC	1 063.9	0.4	0.314
Compostilla 3	ES	STUR	HRD	323.3	0.35	0.336
Compostilla 4	ES	STUR	HRD	341.1	0.35	0.347
Compostilla 5	ES	STUR	HRD	340.6	0.35	0.347
El Fangal 1	ES	COMC	GAS	418.2	0.38	0.565
El Fangal 2	ES	COMC	GAS	417.8	0.38	0.565
El Fangal 3	ES	COMC	GAS	412.7	0.38	0.565
Escombreras 6	ES	COMC	GAS	815.6	0.38	0.565
Escatron Peaker 2	ES	COMC	GAS	274.6	0.325	0.575
Escatron Peaker 3	ES	COMC	GAS	804.3	0.325	0.579
Escombreras 1	ES	COMC	GAS	402.6	0.38	0.565
Escombreras 2	ES	COMC	GAS	401.3	0.38	0.565
Escombreras 3	ES	COMC	GAS	395.2	0.38	0.565
Gibraltar-San Roque 1	ES	COMC	GAS	0	0.38	0.565
Gibraltar-San Roque 2	ES	COMC	GAS	0	0.38	0.565
Guardo 1	ES	STUR	HRD	143.4	0.35	0.336
Guardo 2	ES	STUR	HRD	342.4	0.35	0.347
Huelva-Colon 4	ES	COMC	GAS	390.9	0.38	0.565
La Pereda	ES	STUR	HRD	50	0.35	0.294
La Robla 1	ES	STUR	HRD	263.9	0.35	0.336
La Robla 2	ES	STUR	HRD	355.1	0.35	0.347
Lada 4	ES	STUR	HRD	347.7	0.35	0.347
Litoral de Almeria 1	ES	STUR	HRD	557.5	0.35	0.371
Litoral de Almeria 2	ES	STUR	HRD	562	0.35	0.371
Los Barrios	ES	STUR	HRD	570	0.35	0.371
Malaga-Campanillas	ES	COMC	GAS	415.5	0.325	0.59
Meirama	ES	STUR	HRD	557.2	0.35	0.371
Narcea 2	ES	STUR	HRD	154.3	0.35	0.336
Narcea 3	ES	STUR	HRD	347.4	0.35	0.347
Palos de la Frontera 2	ES	COMC	GAS	389.1	0.38	0.565
Palos de la Frontera 3	ES	COMC	GAS	391	0.38	0.565
Palos de la Frontera 1	ES	COMC	GAS	386.7	0.38	0.565
Plana del Vent 1	ES	COMC	GAS	420.1	0.325	0.579
Plana del Vent 2	ES	COMC	GAS	414	0.325	0.579
Puente Nuevo 3	ES	STUR	HRD	299.7	0.35	0.347
Puerto de Barcelona 1	ES	COMC	GAS	434.8	0.325	0.59
Puerto de Barcelona 2	ES	COMC	GAS	431.4	0.325	0.59
Sabon 3	ES	COMC	GAS	391.3	0.325	0.579
Sagunto 1	ES	COMC	GAS	409.7	0.325	0.579
Sagunto 2	ES	COMC	GAS	411.8	0.325	0.579
Sagunto 3	ES	COMC	GAS	410.6	0.325	0.579
San Roque 1	ES	COMC	GAS	389.8	0.38	0.565
San Roque 2	ES	COMC	GAS	401.8	0.38	0.565
SM de Garona	ES	STUR	NUC	0	0.4	0.314

Unit	**Zone**	**Technology**	**Fuel**	**Capacity (MW)**	**Minimum power output (%)**	**Efficiency (%)**
Santurce 4	ES	COMC	GAS	396.4	0.38	0.565
Soto de Ribeira 4	ES	COMC	GAS	426	0.325	0.579
Soto De Ribera 3	ES	STUR	HRD	346.2	0.35	0.347
Soto de Ribera 5	ES	COMC	GAS	428.1	0.325	0.579
Tarragona Dow	ES	COMC	GAS	385.8	0.4	0.405
Tarragona Basf	ES	COMC	GAS	416.9	0.4	0.405
Teruel 1	ES	STUR	LIG	352.2	0.005215	0.347
Teruel 2	ES	STUR	LIG	352.1	0.005215	0.347
Teruel 3	ES	STUR	LIG	351.4	0.005215	0.347
Trillo 1	ES	STUR	NUC	1003.4	0.4	0.314
Vandellos	ES	STUR	NUC	1045.3	0.4	0.314
Compostilla 2	ES	STUR	HRD	147	0.35	0.285
Lada 3	ES	STUR	HRD	160	0.35	0.336
Soto de Ribera 2	ES	STUR	HRD	254	0.35	0.336
Elcogas	ES	COMC	HRD	335	0.45	0.421
Biogas cluster	ES	STUR	BIO	255.9	0	1
Wind ES cluster	ES	WTON	WIN	22 828.1	0	1
Sun ES cluster	ES	PHOT	SUN	6 719.9	0	1
Oil cluster	ES	STUR	OIL	736	0	1
Biomass ES **cluster**	ES	STUR	BIO	550.5	0.2	0.39
Waste **cluster**	ES	STUR	WST	536.1	0	1
NG Cogen **cluster**	ES	STUR	GAS	5 877	0	1
Norte ES **cluster**	ES	HDAM	WAT	2 529.1	0	1
Tajo ES **cluster**	ES	HDAM	WAT	2 915	0	1
Duero ES **cluster**	ES	HDAM	WAT	3 892.4	0	1
Ebro **cluster**	ES	HDAM	WAT	3 912.6	0	1
Guadiana **cluster**	ES	HDAM	WAT	235.2	0	1
Jucar/Segura **cluster**	ES	HDAM	WAT	2 336.2	0	1
Guadalquivir **cluster**	ES	HDAM	WAT	708	0	1
C.I. de Cataluna **cluster**	ES	HDAM	WAT	288.9	0	1
Mino **cluster**	ES	HDAM	WAT	2 851.1	0	1
C.M. Andaluza **cluster**	ES	HDAM	WAT	407.5	0	1
Lares Figueira da Foz 1	PT	COMC	GAS	435	0.325	0.579
Lares Figueira da Foz 2	PT	COMC	GAS	435	0.325	0.579
Ribatejo 1	PT	COMC	GAS	392	0.38	0.565
Ribatejo 2	PT	COMC	GAS	392	0.38	0.565
Ribatejo 3	PT	COMC	GAS	392	0.38	0.565
Tapada do Outeiro 1	PT	COMC	GAS	344	0.38	0.501
Tapada do Outeiro 2	PT	COMC	GAS	344	0.38	0.501
Tapada do Outeiro 3	PT	COMC	GAS	344	0.38	0.501
Sines 1	PT	STUR	HRD	295	0.35	0.347
Sines 2	PT	STUR	HRD	295	0.35	0.347
Sines 3	PT	STUR	HRD	295	0.35	0.347
Sines 4	PT	STUR	HRD	295	0.35	0.347

Unit	Zone	Technology	Fuel	Capacity (MW)	Minimum power output (%)	Efficiency (%)
Pego 1-2	PT	STUR	HRD	576	0.35	0.347
Pego 3-4	PT	COMC	GAS	837.2	0.325	0.59
Biomass PT **cluster**	PT	STUR	BIO	613	0.2	0.39
Wind PT **cluster**	PT	WTON	WIN	4 826	0	1
Sun PT **cluster**	PT	PHOT	SUN	429	0	1
Other **cluster**	PT	STUR	WST	65	0	1
Gas cluster	PT	COMC	GAS	782.8	0.366	0.544
Tajo PT **cluster**	PT	HDAM	WAT	5 95.1	0	1
Duero PT **cluster**	PT	HDAM	WAT	2 584.9	0	1
Ribeiras south **cluster**	PT	HDAM	WAT	529.6	0	1
Ribeiras north **cluster**	PT	HDAM	WAT	1 581.2	0	1
Ribeiras central **cluster**	PT	HDAM	WAT	565.9	0	1
RoH **cluster**	PT	HDAM	WAT	282.3	0	1

Source: REE, REN, JRC 2017.

Table 11. Techno-economic features II of the generating units considered in the Iberian Peninsula for the Dispa-SET UCD model.

Unit	Minimum up time (h)	Minimum down time (h)	Ramp up rate (%/min)	Ramp down rate (%/min)	Start-up cost (€)	Efficiency at minimum load (%)	Start-up time (h)	CO_2 intensity (ton CO_2/MWh)
Abono 1	10	9	0.006	0.006	60 534	0.336	4	1.014
Abono 2	10	9	0.006	0.006	50 384	0.371	4	0.918
Aceca CC3	2	2	0.01	0.01	22 002	0.565	2	0.357
Aceca CC4	2	2	0.01	0.01	21 261	0.565	2	0.357
Almaraz 1	88	27	0.0512	0.0512	1 011 000	0.314	7	0
Almaraz 2	88	27	0.0512	0.0512	1 006 000	0.314	7	0
Amorebieta	2	2	0.01	0.01	44 802	0.565	2	0.357
Anllares	10	9	0.006	0.006	61 419	0.347	4	0.981
Arcos de la Frontera 3	2	2	0.01	0.01	46 911	0.565	2	0.357
Arcos de la Frontera 1	2	2	0.01	0.01	22 173	0.565	2	0.357
Arcos de la Frontera 2	2	2	0.01	0.01	21 261	0.565	2	0.357
Arrubal 1	2	2	0.01	0.01	22 515	0.565	2	0.357
Arrubal 2	2	2	0.01	0.01	22 230	0.565	2	0.357
PG Rodriguez 1	10	9	0.006	0.006	62 127	0.336	4	1.014
PG Rodriguez 2	10	9	0.006	0.006	62 127	0.347	4	0.981
PG Rodriguez 3	10	9	0.006	0.006	61 950	0.347	4	0.981
PG Rodriguez 4	10	9	0.006	0.006	62 127	0.347	4	0.981
PG Rodriguez 5	2	2	0.01	0.01	48 792	0.579	2	0.349
Asco 1	88	27	0.0512	0.0512	996 000	0.314	7	0
Asco 2	88	27	0.0512	0.0512	992 000	0.314	7	0
Bahia de Algeciras II	2	2	0.01	0.01	46 797	0.59	2	0.343
Bahia de Bizkaia	2	2	0.01	0.01	44 745	0.565	2	0.357
Besos 3	2	2	0.01	0.01	23 484	0.565	2	0.357
Besos 4	2	2	0.01	0.01	22 800	0.565	2	0.357
Besos 5	2	2	0.01	0.01	48 963	0.579	2	0.349
Castejon 3	2	2	0.01	0.01	23 826	0.565	2	0.357
Castejon 1	2	2	0.01	0.01	24 225	0.565	2	0.357
Castejon 2	2	2	0.01	0.01	21 603	0.579	2	0.349
Castelnou 3	2	2	0.01	0.01	44 574	0.565	2	0.357
Castellon 4	2	2	0.01	0.01	47 823	0.579	2	0.349
Castelnou	2	2	0.01	0.01	45 087	0.565	2	0.357
Cofrentes Nuclear	88	27	0.0512	0.0512	1 064 000	0.314	7	0
Compostilla 3	10	9	0.006	0.006	57 171	0.336	4	1.014
Compostilla 4	10	9	0.006	0.006	60 357	0.347	4	0.981
Compostilla 5	10	9	0.006	0.006	60 357	0.347	4	0.981
El Fangal 1	2	2	0.01	0.01	23 826	0.565	2	0.357
El Fangal 2	2	2	0.01	0.01	23 826	0.565	2	0.357
El Fangal 3	2	2	0.01	0.01	23 541	0.565	2	0.357
Escombreras 6	2	2	0.01	0.01	46 512	0.565	2	0.357
Escatron Peaker 2	2	2	0.01	0.01	15 675	0.575	2	0.351
Escatron Peaker 3	2	2	0.01	0.01	45 600	0.579	2	0.349

Unit	Minimum up time (h)	Minimum down time (h)	Ramp up rate (% / min)	Ramp down rate (% / min)	Start-up cost (€)	Efficiency at minimum load (%)	Start-up time (h)	CO_2 intensity (ton CO_2 / MWh)
Escombreras 1	2	2	0.01	0.01	22 971	0.565	2	0.357
Escombreras 2	2	2	0.01	0.01	22 857	0.565	2	0.357
Escombreras 3	2	2	0.01	0.01	22 515	0.565	2	0.357
Gibraltar-San Roque 1	2	2	0.01	0.01	22 230	0.565	2	0.357
Gibraltar-San Roque 2	2	2	0.01	0.01	22 914	0.565	2	0.357
Guardo 1	10	9	0.006	0.006	25 311	0.336	4	1.014
Guardo 2	10	9	0.006	0.006	60 534	0.347	4	0.981
Huelva-Colon 4	2	2	0.01	0.01	22 287	0.565	2	0.357
La Pereda	10	9	0.006	0.006	8 850	0.294	4	1.157
La Robla 1	10	9	0.006	0.006	46 728	0.336	4	1.014
La Robla 2	10	9	0.006	0.006	62 835	0.347	4	0.981
Lada 4	10	9	0.006	0.006	61 596	0.347	4	0.981
Litoral de Almeria 1	10	9	0.006	0.006	52 452	0.371	4	0.918
Litoral de Almeria 2	10	9	0.006	0.006	52 828	0.371	4	0.918
Los Barrios	10	9	0.006	0.006	53 580	0.371	4	0.918
Malaga-Campanillas	2	2	0.01	0.01	23 712	0.59	2	0.343
Meirama	10	9	0.006	0.006	52 358	0.371	4	0.918
Narcea 2	10	9	0.006	0.006	27 258	0.336	4	1.014
Narcea 3	10	9	0.006	0.006	61 419	0.347	4	0.981
Palos de la Frontera 2	2	2	0.01	0.01	22 173	0.565	2	0.357
Palos de la Frontera 3	2	2	0.01	0.01	22 287	0.565	2	0.357
Palos de la Frontera 1	2	2	0.01	0.01	22 059	0.565	2	0.357
Plana del Vent 1	2	2	0.01	0.01	23 940	0.579	2	0.349
Plana del Vent 2	2	2	0.01	0.01	23 598	0.579	2	0.349
Puente Nuevo 3	10	9	0.006	0.006	53 100	0.347	4	0.981
Puerto de Barcelona 1	2	2	0.01	0.01	24 795	0.59	2	0.343
Puerto de Barcelona 2	2	2	0.01	0.01	24 567	0.59	2	0.343
Sabon 3	2	2	0.01	0.01	22 287	0.579	2	0.349
Sagunto 1	2	2	0.01	0.01	23 370	0.579	2	0.349
Sagunto 2	2	2	0.01	0.01	23 484	0.579	2	0.349
Sagunto 3	2	2	0.01	0.01	23 427	0.579	2	0.349
San Roque 1	2	2	0.01	0.01	22 230	0.565	2	0.357
San Roque 2	2	2	0.01	0.01	22 914	0.565	2	0.357
SM de Garona	88	27	0.0512	0.0512	1 011 000	0.314	7	0
Santurce 4	2	2	0.01	0.01	22 572	0.565	2	0.357
Soto de Ribeira 4	2	2	0.01	0.01	24 282	0.579	2	0.349
Soto De Ribera 3	10	9	0.006	0.006	61 242	0.347	4	0.981
Soto de Ribera 5	2	2	0.01	0.01	24 396	0.579	2	0.349
Tarragona Dow	2	2	0.01	0.01	22 002	0.405	2	0.499
Tarragona Basf	2	2	0.01	0.01	23 769	0.405	2	0.499
Teruel 1	14	9	0.0036	0.0036	62 304	0.347	6	1.047
Teruel 2	14	9	0.0036	0.0036	62 304	0.347	6	1.047

Unit	**Minimum up time (h)**	**Minimum down time (h)**	**Ramp up rate (%/min)**	**Ramp down rate (%/min)**	**Start-up cost (€)**	**Efficiency at minimum load (%)**	**Start-up time (h)**	**CO_2 intensity (ton CO_2/MWh)**
Teruel 3	14	9	0.0036	0.0036	62 127	0.347	6	1.047
Trillo 1	88	27	0.0512	0.0512	1 003 000	0.314	7	0
Vandellos	88	27	0.0512	0.0512	1 045 000	0.314	7	0
Compostilla 2	10	9	0.006	0.006	24 426	0.285	4	1.195
Lada 3	10	9	0.006	0.006	27 435	0.336	4	1.014
Soto de Ribera 2	10	9	0.006	0.006	42 303	0.336	4	1.014
Elcogas	2	2	0.01	0.01	16 872	0.421	2	0.809
Biogas **cluster**	1	1	0.2	0.2	0	0.5	1	0
Wind ES **cluster**	1	1	0.2	0.2	0	0.5	1	0
Sun ES **cluster**	1	1	0.2	0.2	0	0.5	1	0
Oil **cluster**	1	1	0.2	0.2	0	0.5	1	0
Biomass ES **cluster**	1	1	0.04	0.05	10 728	0.195	1	0
Waste **cluster**	1	1	0.2	0.2	0	1	1	0
NG Cogen **cluster**	1	1	0.2	0.2	0	0.5	1	0
Norte ES **cluster**	1	1	0.2	0.2	0	0.5	1	0
Tajo ES **cluster**	1	1	0.2	0.2	0	0.5	1	0
Duero ES **cluster**	1	1	0.2	0.2	0	0.5	1	0
Ebro **cluster**	1	1	0.2	0.2	0	0.5	1	0
Guadiana **cluster**	1	1	0.2	0.2	0	0.5	1	0
Jucar/Segura **cluster**	1	1	0.2	0.2	0	0.5	1	0
Guadalquivir cluster	1	1	0.2	0.2	0	0.5	1	0
C.I. de Cataluna cluster	1	1	0.2	0.2	0	0.5	1	0
Mino **cluster**	1	1	0.2	0.2	0	0.5	1	0
C.M. Andaluza cluster	1	1	0.2	0.2	0	0.5	1	0
Lares Figueira da Foz 1	2	2	0.01	0.01	24 567	0.579	2	0.349
Lares Figueira da Foz 2	2	2	0.01	0.01	24 567	0.579	2	0.349
Ribatejo 1	2	2	0.01	0.01	22 344	0.565	2	0.357
Ribatejo 2	2	2	0.01	0.01	22 344	0.565	2	0.357
Ribatejo 3	2	2	0.01	0.01	22 344	0.565	2	0.357
Tapada do Outeiro 1	3	4	0.01	0.01	19 095	0.501	3	0.403
Tapada do Outeiro 2	3	4	0.01	0.01	19 095	0.501	3	0.403
Tapada do Outeiro 3	3	4	0.01	0.01	19 095	0.501	3	0.403
Sines 1	10	9	0.006	0.006	54 516	0.347	4	0.981
Sines 2	10	9	0.006	0.006	55 578	0.347	4	0.981
Sines 3	10	9	0.006	0.006	55 578	0.347	4	0.981
Sines 4	10	9	0.006	0.006	55 578	0.347	4	0.981
Pego 1-2	10	9	0.006	0.006	55 578	0.347	4	0.981
Pego 3-4	2	2	0.01	0.01	23 655	0.59	2	0.343
Biomass PT **cluster**	1	1	0.04	0.05	10 728	0.195	1	0
Wind PT **cluster**	1	1	0.2	0.2	0	0.5	1	0
Sun PT **cluster**	1	1	0.2	0.2	0	0.5	1	0
Other **cluster**	1	1	0.2	0.2	0	0.5	1	0
Gas **cluster**	2	3	0.01	0.01	21 681	0.56	2	0.372

Unit	Minimum up time (h)	Minimum down time (h)	Ramp up rate (% / min)	Ramp down rate (% / min)	Start-up cost (€)	Efficiency at minimum load (%)	Start-up time (h)	CO_2 intensity (ton CO_2 / MWh)
***Tajo PT* cluster**	1	1	0.2	0.2	0	0.5	1	0
***Duero PT* cluster**	1	1	0.2	0.2	0	0.5	1	0
***Ribeiras south* cluster**	1	1	0.2	0.2	0	0.5	1	0
***Ribeiras north* cluster**	1	1	0.2	0.2	0	0.5	1	0
***Ribeiras central* cluster**	1	1	0.2	0.2	0	0.5	1	0
***RoH* cluster**	1	1	0.2	0.2	0	0.5	1	0

Source: JRC 2017.

Table 12. Techno-economic features III of the generating units considered in the Iberian Peninsula for the Dispa-SET UCD model.

Unit	Withdrawal factor (m^3/MW)	Unit	Withdrawal factor (m^3/MW)
Abono 1	102.5	***Lada 4***	102.5
Abono 2	102.5	***Litoral de Almeria 1***	102.5
Aceca CC3	43.1	***Litoral de Almeria 2***	102.5
Aceca CC4	1.0	***Los Barrios***	102.5
Almaraz 1	167.9	***Malaga-Campanillas***	1.0
Almaraz 2	167.9	***Meirama***	2.2
Amorebieta	0.0	***Narcea 2***	102.5
Anllares	2.2	***Narcea 3***	102.5
Arcos de la Frontera 3	1.0	***Palos de la Frontera 2***	43.1
Arcos de la Frontera 1	1.0	***Palos de la Frontera 3***	43.1
Arcos de la Frontera 2	1.0	***Palos de la Frontera 1***	43.1
Arrubal 1	0.0	***Plana del Vent 1***	1.0
Arrubal 2	0.0	***Plana del Vent 2***	1.0
PG Rodriguez 1	2.2	***Puente Nuevo 3***	102.5
PG Rodriguez 2	2.2	***Puerto de Barcelona 1***	1.0
PG Rodriguez 3	2.2	***Puerto de Barcelona 2***	1.0
PG Rodriguez 4	2.2	***Sabon 3***	43.1
PG Rodriguez 5	1.0	***Sagunto 1***	1.0
Asco 1	167.9	***Sagunto 2***	1.0
Asco 2	167.9	***Sagunto 3***	1.0
Bahia de Algeciras II	43.1	***San Roque 1***	1.0
Bahia de Bizkaia	43.1	***San Roque 2***	1.0
Besos 3	43.1	***SM de Garona***	167.9
Besos 4	43.1	***Santurce 4***	43.1
Besos 5	43.1	***Soto de Ribeira 4***	43.1
Castejon 3	1.0	***Soto De Ribera 3***	102.5
Castejon 1	1.0	***Soto de Ribera 5***	43.1
Castejon 2	1.0	***Tarragona Dow***	1.0
Castelnou 3	43.1	***Tarragona Basf***	
Castellon 4	43.1	***Teruel 1***	2.2
Castelnou	0.0	***Teruel 2***	2.2
Cofrentes Nuclear	4.2	***Teruel 3***	2.2
Compostilla 3	102.5	***Trillo 1***	4.2
Compostilla 4	102.5	***Vandellos***	167.9
Compostilla 5	102.5	***Compostilla 2***	102.5
El Fangal 1	1.0	***Lada 3***	102.5
El Fangal 2	1.0	***Soto de Ribera 2***	102.5
El Fangal 3	1.0	***Lares Figueira da Foz 1***	1.0
Escombreras 6	43.1	***Lares Figueira da Foz 2***	1.0
Escatron Peaker 2		***Ribatejo 1***	1.0
Escatron Peaker 3	43.1	***Ribatejo 2***	1.0
Escombreras 1	1.0	***Ribatejo 3***	1.0
Escombreras 2	1.0	***Tapada do Outeiro 1***	43.1

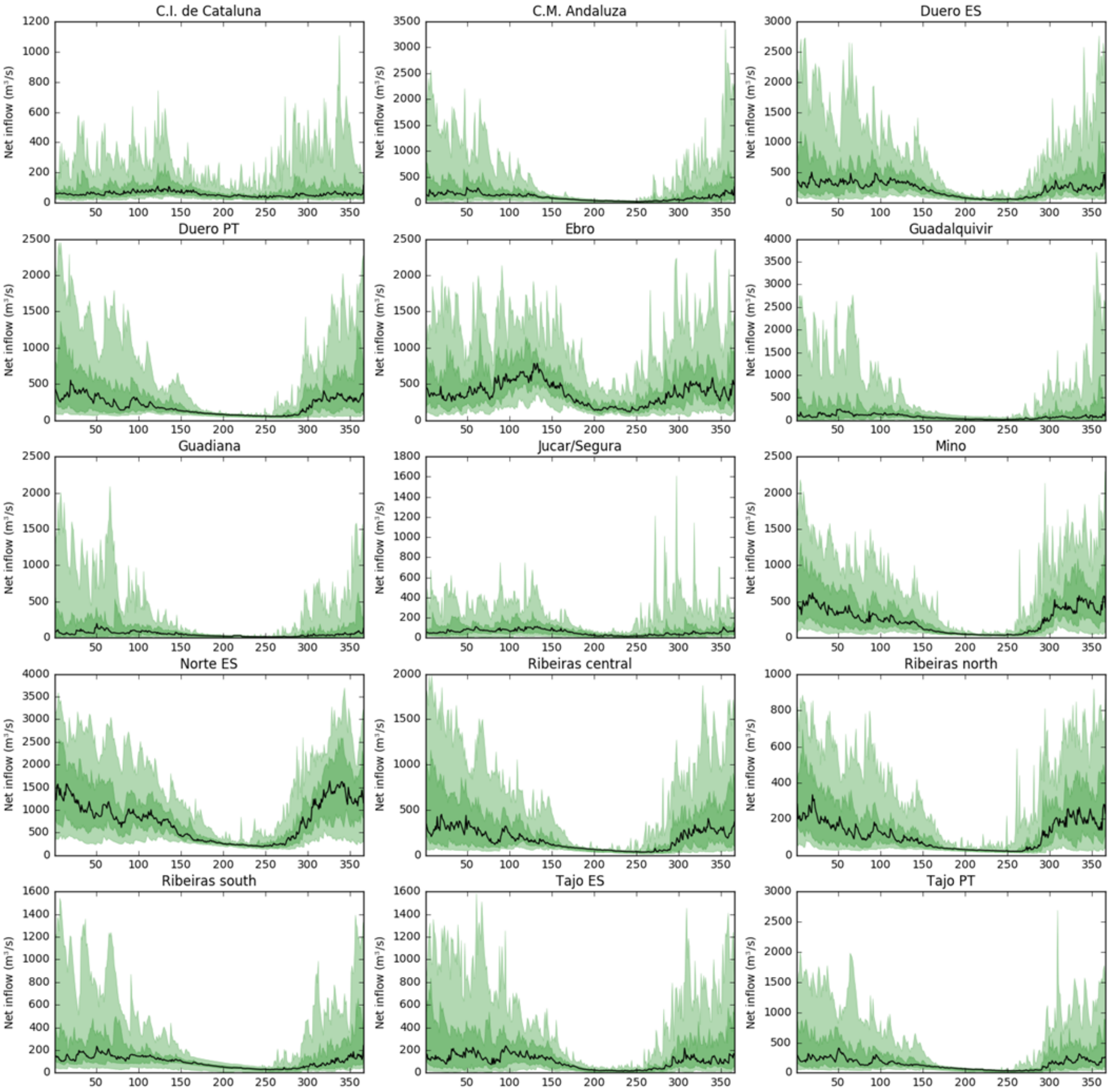
Unit	Withdrawal factor (m^3/MW)	Unit	Withdrawal factor (m^3/MW)
Escombreras 3	1.0	***Tapada do Outeiro 2***	43.1
Gibraltar-San Roque 1		***Tapada do Outeiro 3***	43.1
Gibraltar-San Roque 2		***Sines 1***	102.5
Guardo 1	102.5	***Sines 2***	102.5
Guardo 2	102.5	***Sines 3***	102.5
Huelva-Colon 4	43.1	***Sines 4***	102.5
La Pereda	2.2	***Pego 1-2***	2.2
La Robla 1	2.2	***Pego 3-4***	1.0
La Robla 2	2.2		

Source: Macknick *et al.* [54].

Annex 2. Water inflows for the Iberian Peninsula

This annex presents the historical time series of net inflows in m^3/s for 25 years spanning from 1990 till 2014. Figure 46 shows the 5th, 25th, 50th, 75th, and 95th percentiles of the time series per catchment.

Figure 46. Historical time series of net inflows (m^3/s) for a year per catchment. The 5th, 25th, 50th (black line), 75th, and 95th percentiles are presented.



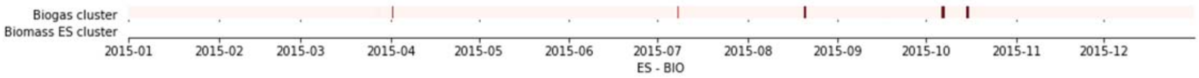
Source: JRC 2017.

Annex 3. Power dispatch and unit commitment for the Iberian Peninsula

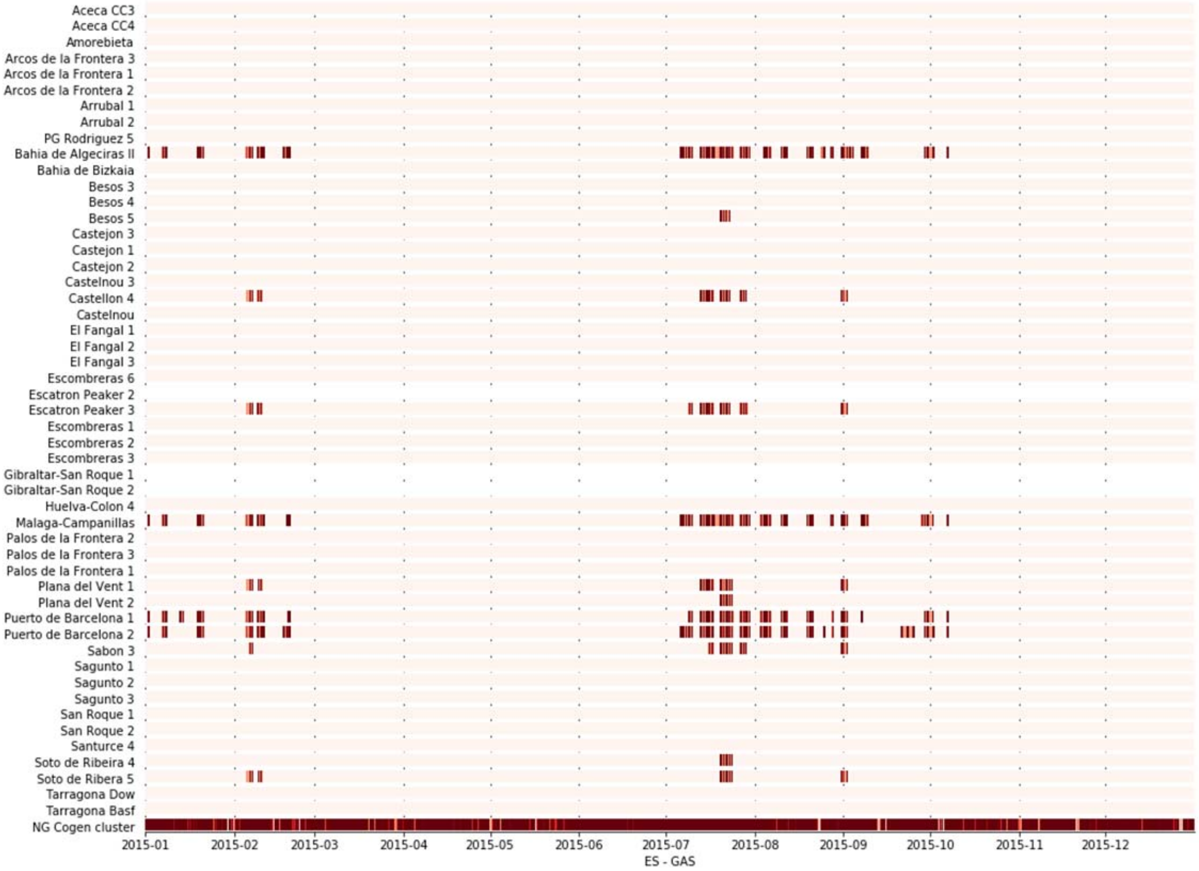
This annex contains the power dispatch and unit commitment for all power plants per country and for each hydrological scenario considered in the scenario-based analysis as a result of Dispa-SET UCD simulations. The figures are further classified per fuel type. Figure 47, Figure 48, and Figure 49 are related to the dispatch and commitment for the dry, average, and wet scenario, respectively. Note that the intensity of the colour is associated with the power dispatch with respect to the maximum capacity of each power plant.

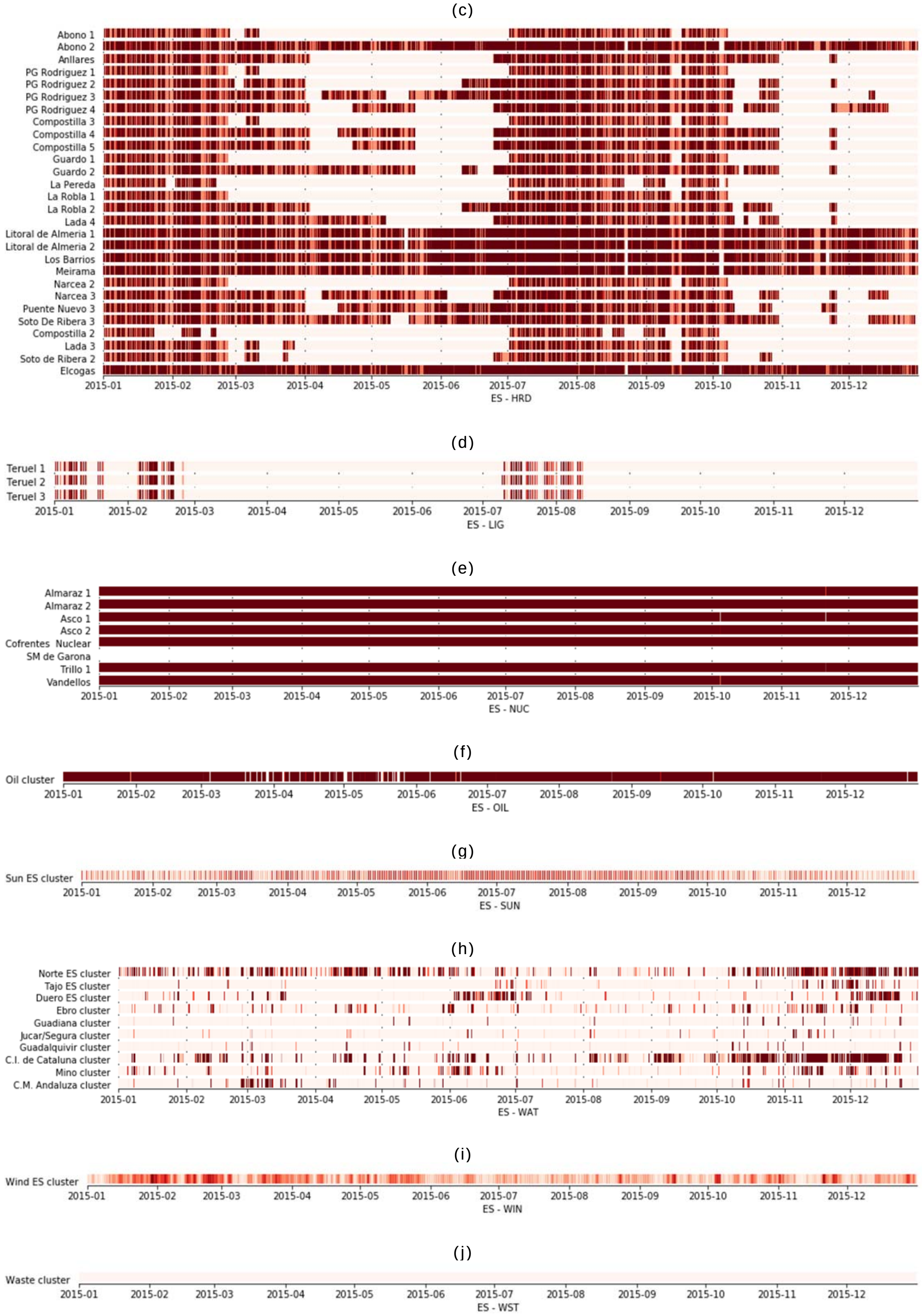
Figure 47. Power dispatch and commitment for the Iberian Peninsula case study for the dry hydrological scenario: (a)-(j) units in Spain (ES), and (k)-(p) units in Portugal (PT).

(a)



(b)




(c)
Abono 1
Abono 2
Anllares
PG Rodriguez 1
PG Rodriguez 2
PG Rodriguez 3
PG Rodriguez 4
Compostilla 3
Compostilla 4
Compostilla 5
Guardo 1
Guardo 2
La Pereda
La Robla 1
La Robla 2
Lada 4
Litoral de Almeria 1
Litoral de Almeria 2
Los Barrios
Meirama
Narcea 2
Narcea 3
Puente Nuevo 3
Soto De Ribera 3
Compostilla 2
Lada 3
Soto de Ribera 2
Elcogas
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - HRD
(d)
Teruel 1
Teruel 2
Teruel 3
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - LIG
(e)
Almaraz 1
Almaraz 2
Asco 1
Asco 2
Cofrentes Nuclear
SM de Garona
Trillo 1
Vandellos
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - NUC
(f)
Oil cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - OIL
(g)
Sun ES cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - SUN
(h)
Norte ES cluster
Tajo ES cluster
Duero ES cluster
Ebro cluster
Guadiana cluster
Jucar/Segura cluster
Guadalquivir cluster
C.I. de Cataluna cluster
Mino cluster
C.M. Andaluza cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - WAT
(i)
Wind ES cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - WIN
(j)
Waste cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - WST

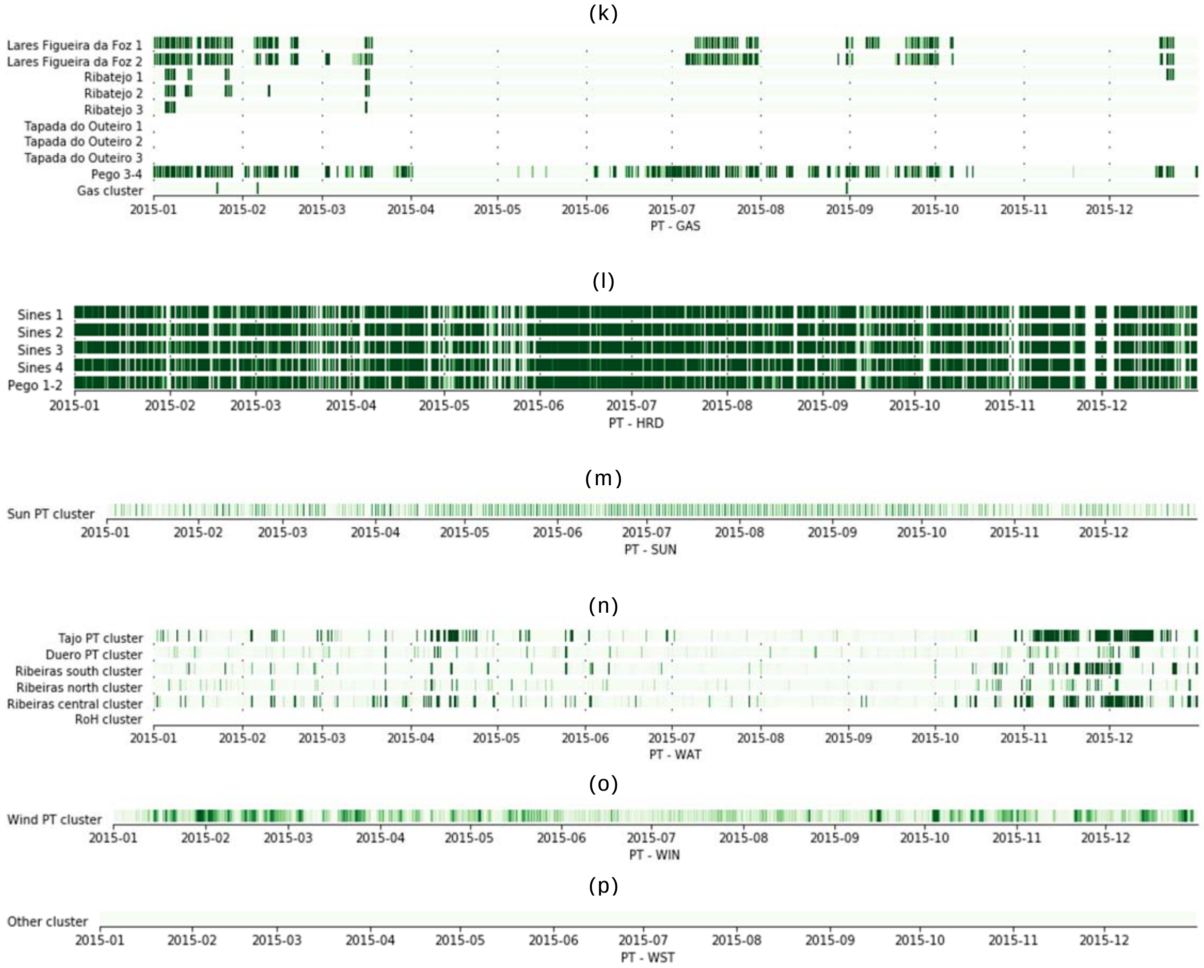
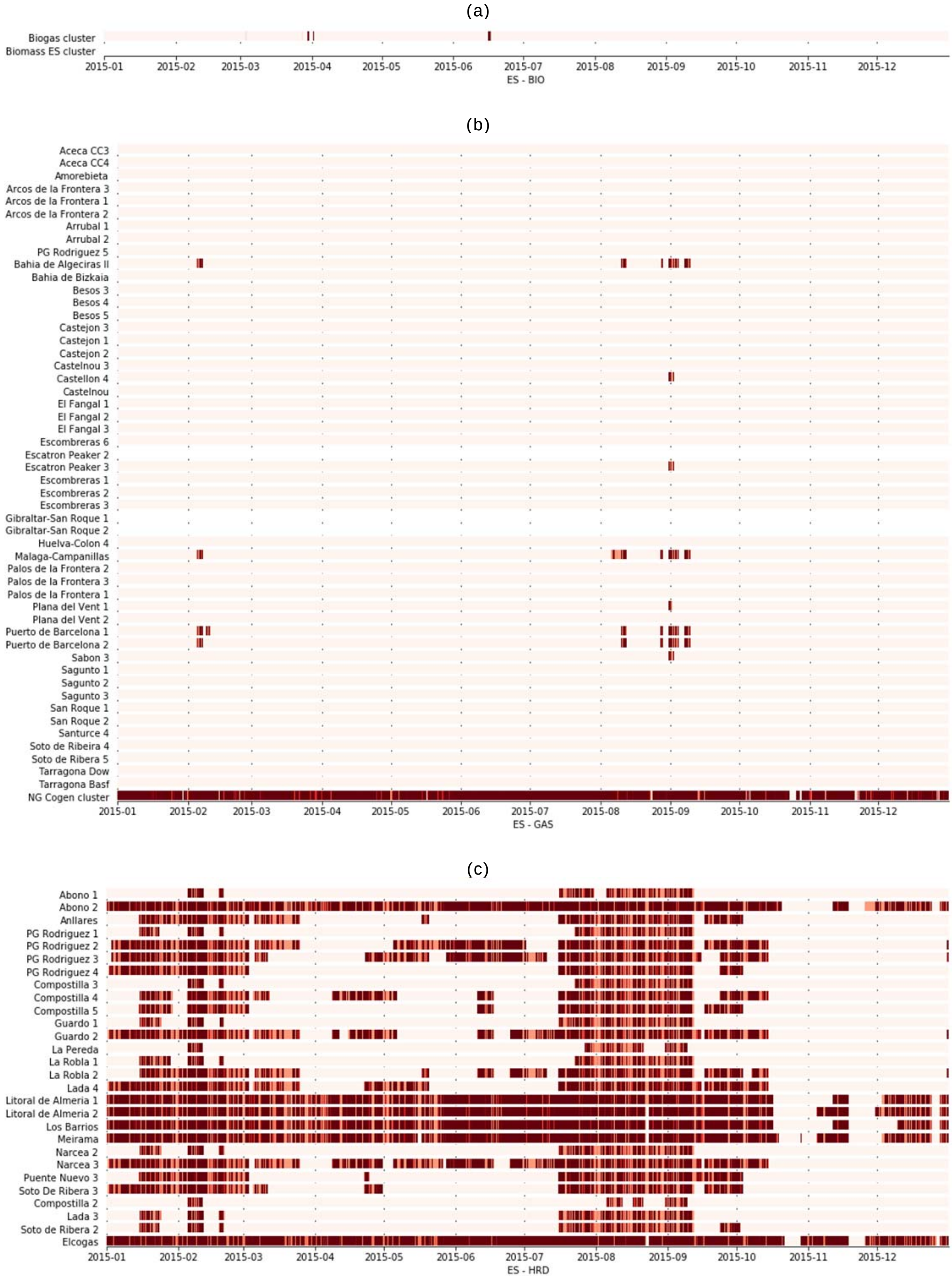
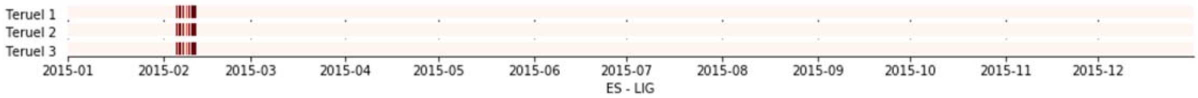

(k)
Lares Figueira da Foz 1
Lares Figueira da Foz 2
Ribatejo 1
Ribatejo 2
Ribatejo 3
Tapada do Outeiro 1
Tapada do Outeiro 2
Tapada do Outeiro 3
Pego 3-4
Gas cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - GAS
(l)
Sines 1
Sines 2
Sines 3
Sines 4
Pego 1-2
PT - HRD
(m)
Sun PT cluster
PT - SUN
(n)
Tajo PT cluster
Duero PT cluster
Ribeiras south cluster
Ribeiras north cluster
Ribeiras central cluster
RoH cluster
PT - WAT
(o)
Wind PT cluster
PT - WIN
(p)
Other cluster
PT - WST

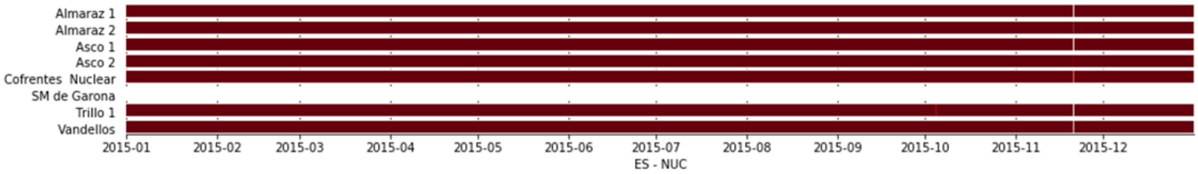
Figure 48. Power dispatch and commitment for the Iberian Peninsula case study for the average hydrological scenario: (a)-(j) units in Spain (ES), and (k)-(p) units in Portugal (PT).



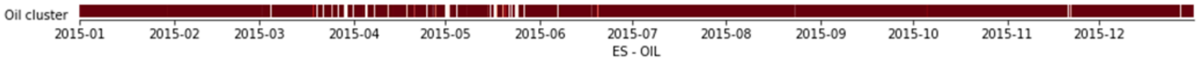
(d)


Teruel 1
Teruel 2
Teruel 3
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - LIG

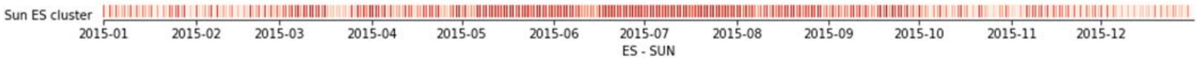
(e)


Almaraz 1
Almaraz 2
Asco 1
Asco 2
Cofrentes Nuclear
SM de Garona
Trillo 1
Vandellos
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - NUC

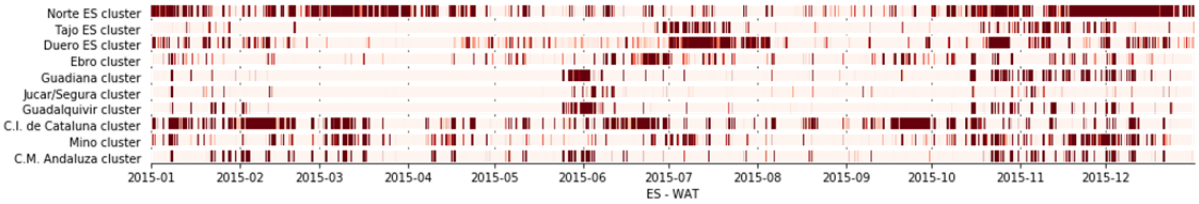
(f)


Oil cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - OIL

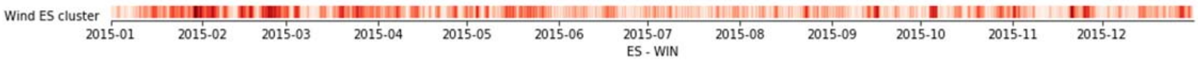
(g)


Sun ES cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - SUN

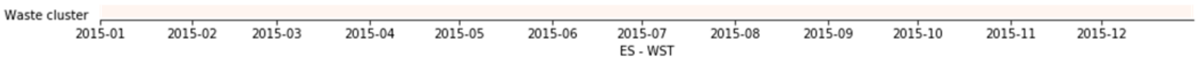
(h)


Norte ES cluster
Tajo ES cluster
Duero ES cluster
Ebro cluster
Guadiana cluster
Jucar/Segura cluster
Guadalquivir cluster
C.I. de Cataluna cluster
Mino cluster
C.M. Andaluza cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - WAT

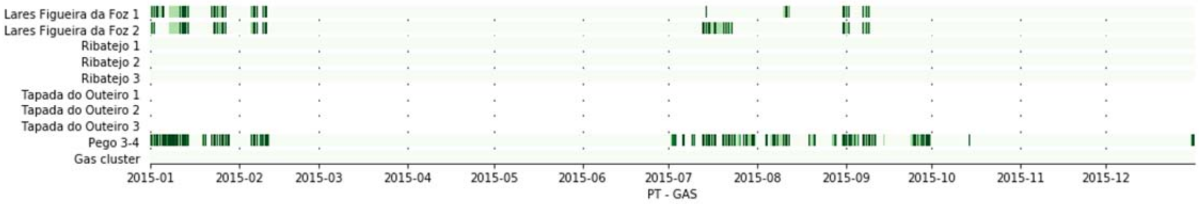
(i)


Wind ES cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - WIN

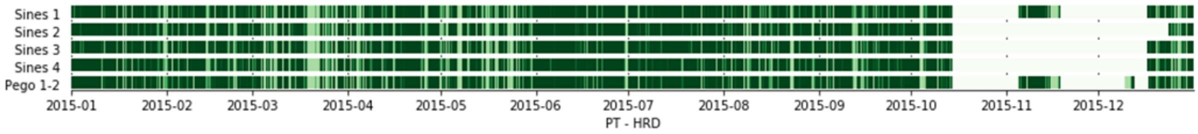
(j)


Waste cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - WST

(k)


Lares Figueira da Foz 1
Lares Figueira da Foz 2
Ribatejo 1
Ribatejo 2
Ribatejo 3
Tapada do Outeiro 1
Tapada do Outeiro 2
Tapada do Outeiro 3
Pego 3-4
Gas cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - GAS

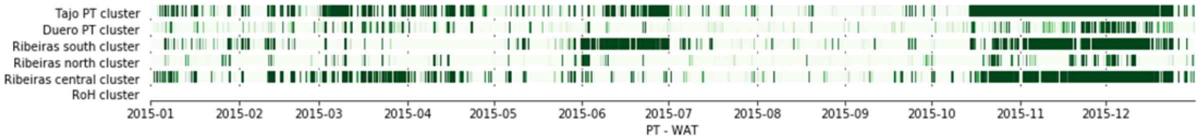
(l)


Sines 1
Sines 2
Sines 3
Sines 4
Pego 1-2
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - HRD

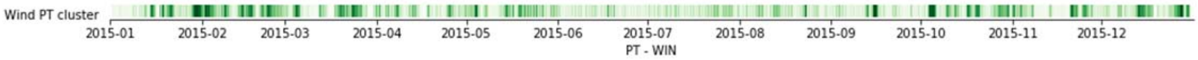
(m)


Sun PT cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - SUN

(n)



(o)

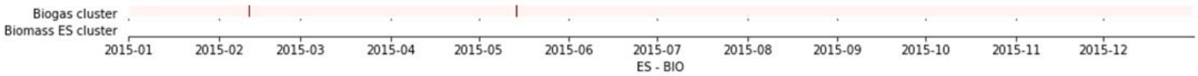


(p)

Source: JRC 2017.

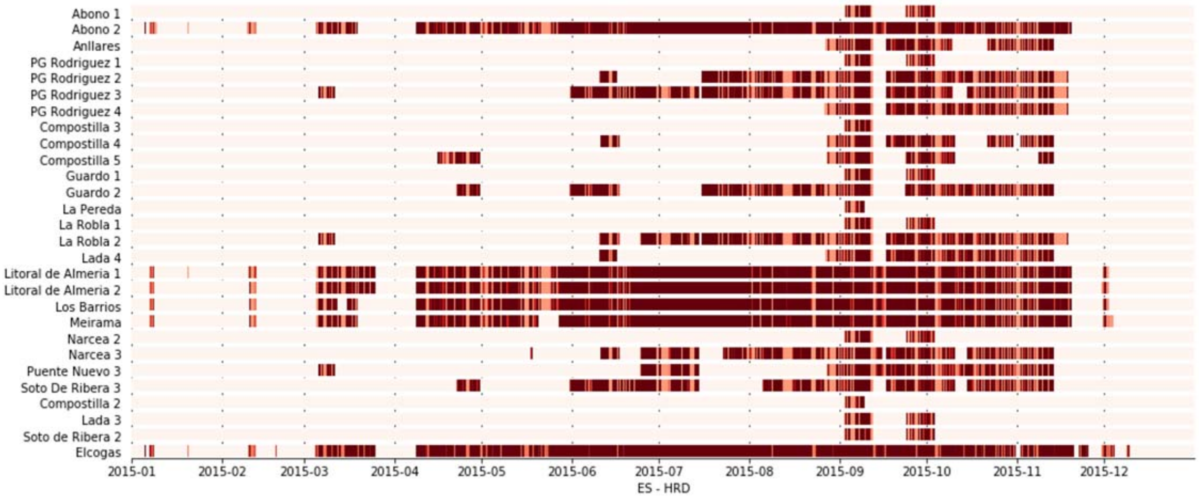
Figure 49. Power dispatch and commitment for the Iberian Peninsula case study for the wet hydrological scenario: (a)-(j) units in Spain (ES), and (k)-(p) units in Portugal (PT).

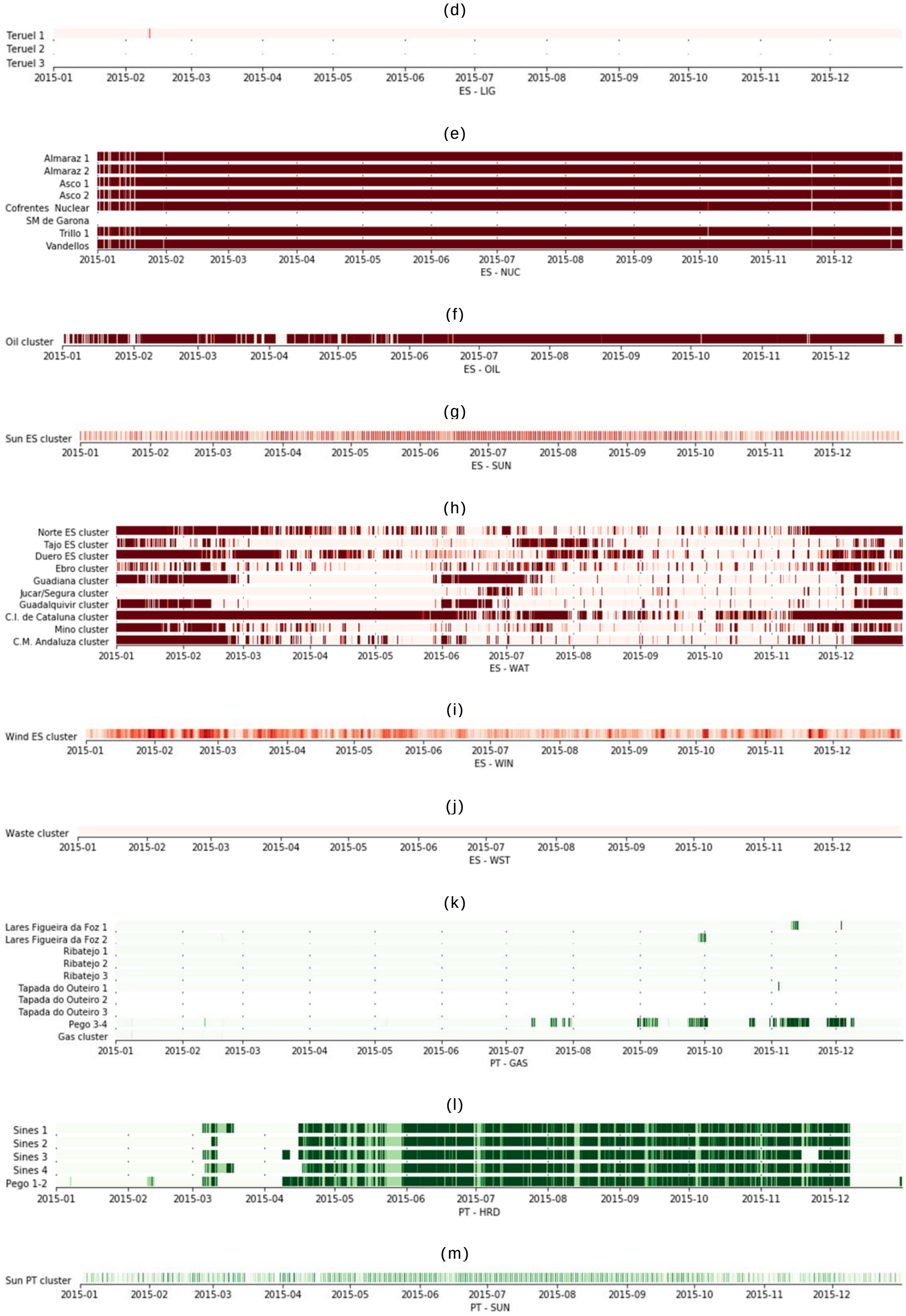
(a)



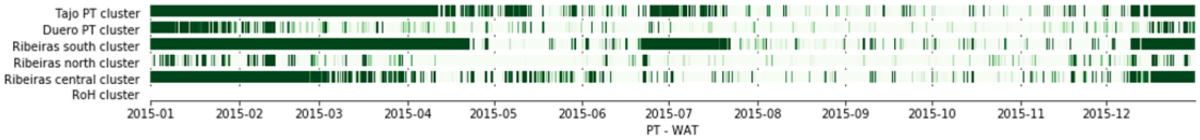
(b)

(c)

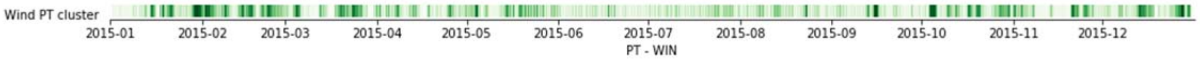



(d)
Teruel 1
Teruel 2
Teruel 3
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
ES - LIG
(e)
Almaraz 1
Almaraz 2
Asco 1
Asco 2
Cofrentes Nuclear
SM de Garona
Trillo 1
Vandellos
ES - NUC
(f)
Oil cluster
ES - OIL
(g)
Sun ES cluster
ES - SUN
(h)
Norte ES cluster
Tajo ES cluster
Duero ES cluster
Ebro cluster
Guadiana cluster
Jucar/Segura cluster
Guadalquivir cluster
C.I. de Cataluna cluster
Mino cluster
C.M. Andaluza cluster
ES - WAT
(i)
Wind ES cluster
ES - WIN
(j)
Waste cluster
ES - WST
(k)
Lares Figueira da Foz 1
Lares Figueira da Foz 2
Ribatejo 1
Ribatejo 2
Ribatejo 3
Tapada do Outeiro 1
Tapada do Outeiro 2
Tapada do Outeiro 3
Pego 3-4
Gas cluster
PT - GAS
(l)
Sines 1
Sines 2
Sines 3
Sines 4
Pego 1-2
PT - HRD
(m)
Sun PT cluster
PT - SUN

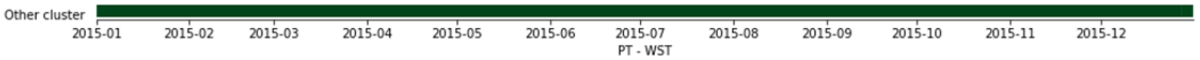
(n)


Tajo PT cluster
Duero PT cluster
Ribeiras south cluster
Ribeiras north cluster
Ribeiras central cluster
RoH cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - WAT

(o)


Wind PT cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - WIN

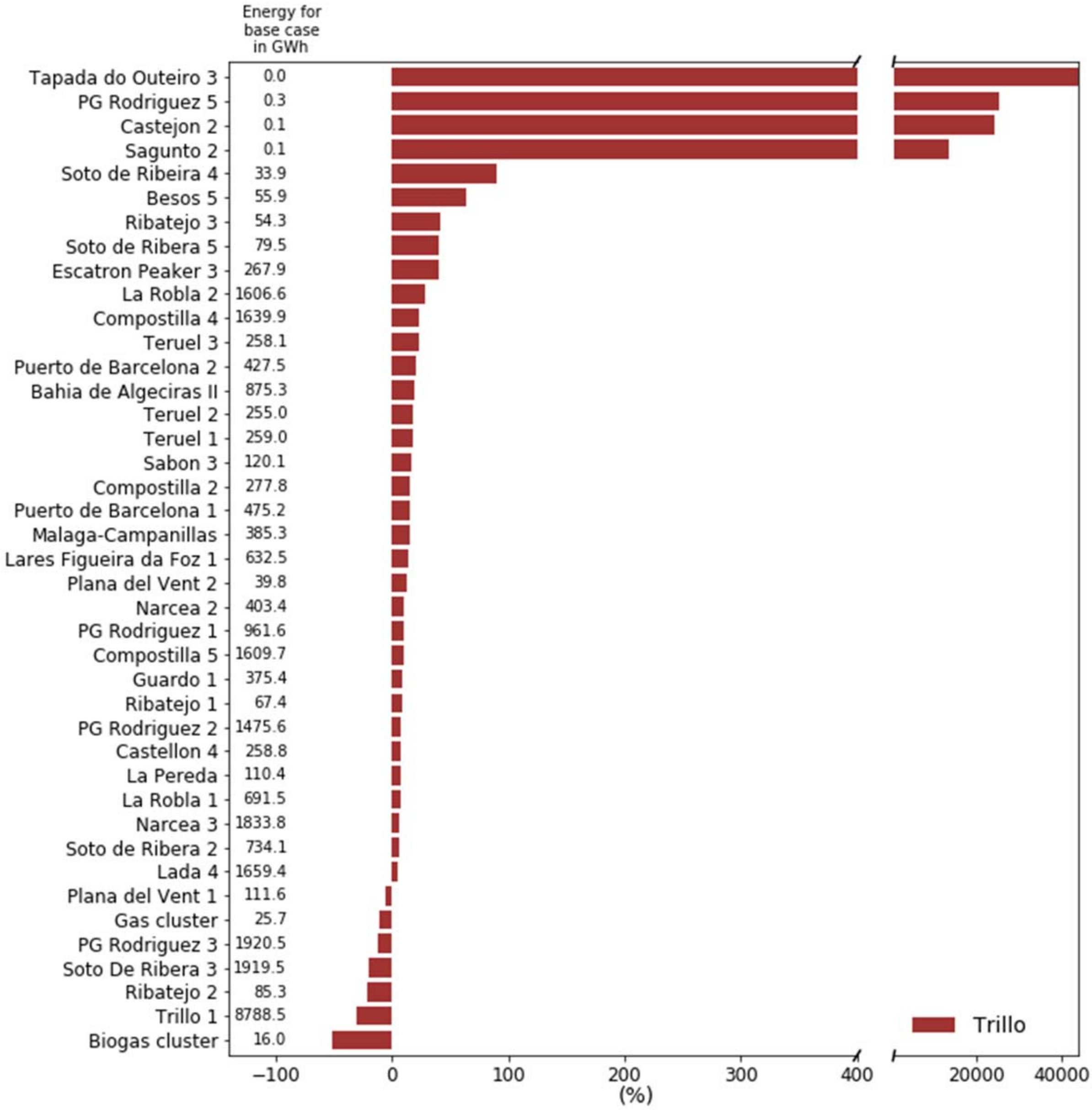
(p)


Other cluster
2015-01
2015-02
2015-03
2015-04
2015-05
2015-06
2015-07
2015-08
2015-09
2015-10
2015-11
2015-12
PT - WST

Annex 4. Variations of energy production

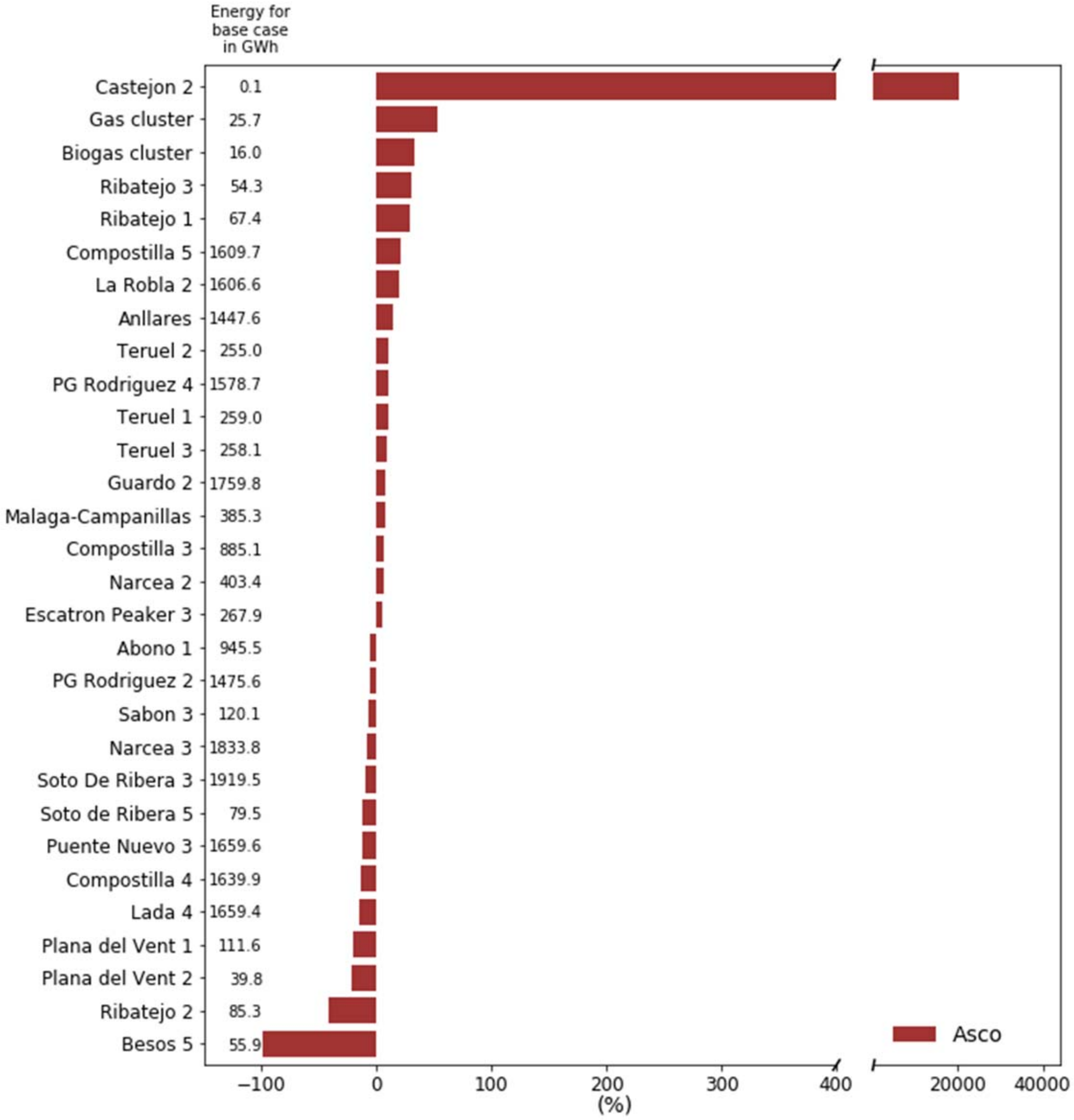
This annex provides additional information about Section 5.4. Variations of annual energy production per power plant with a variation greater than 5 % for the '*Trillo* case', '*Asco* case', '*Teruel* case', and '*Anllares* case' are respectively illustrated in Figure 50, Figure 51, Figure 52, and Figure 53.

Figure 50. Variation of annual energy production per power plant with a variation greater than 5 % for the '*Trillo* case' compared to the 'Base case'.



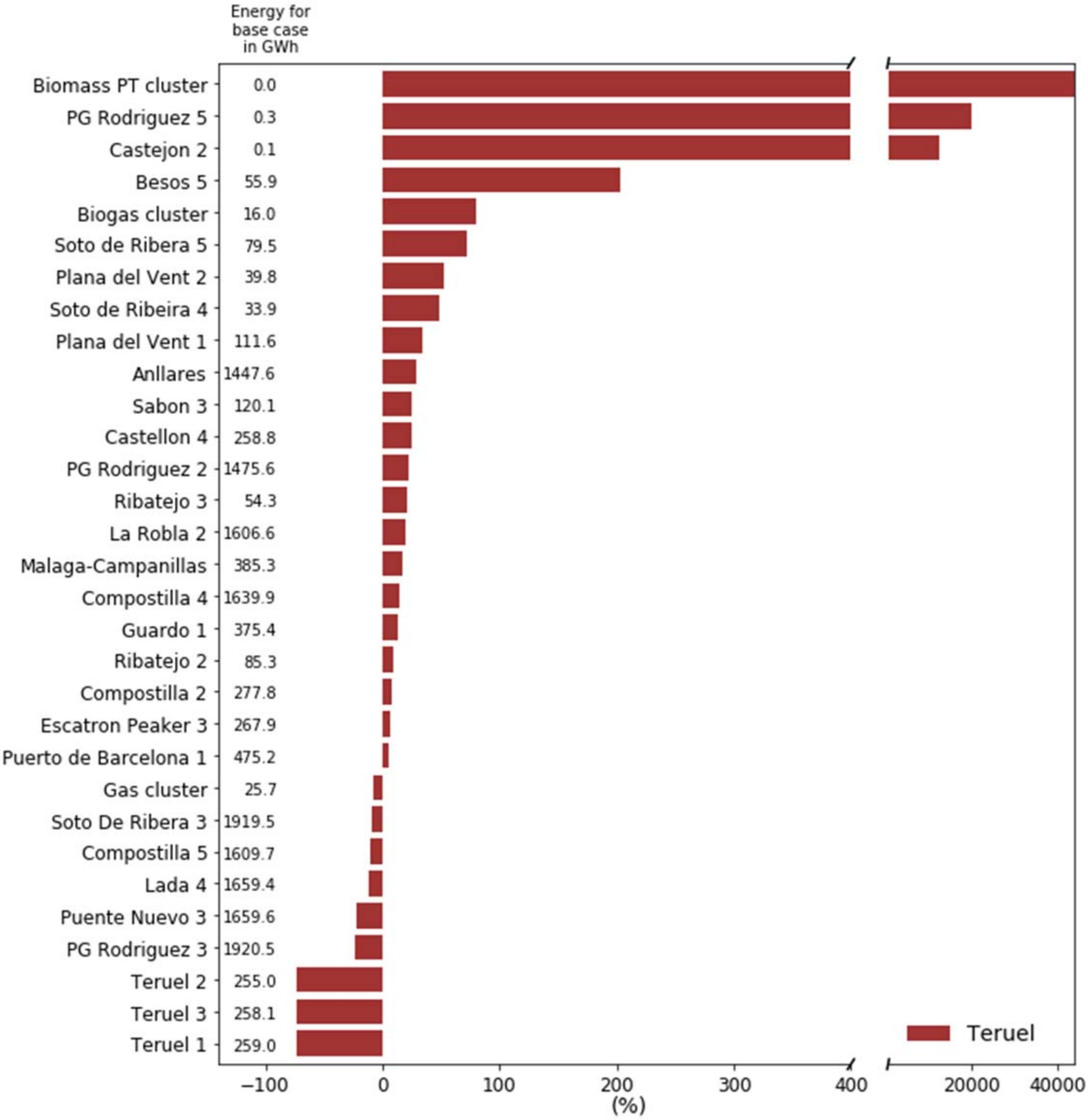
Source: JRC 2017.

Figure 51. Variation of annual energy production per power plant with a variation greater than 5 % for the '*Asco* case' compared to the 'Base case'.



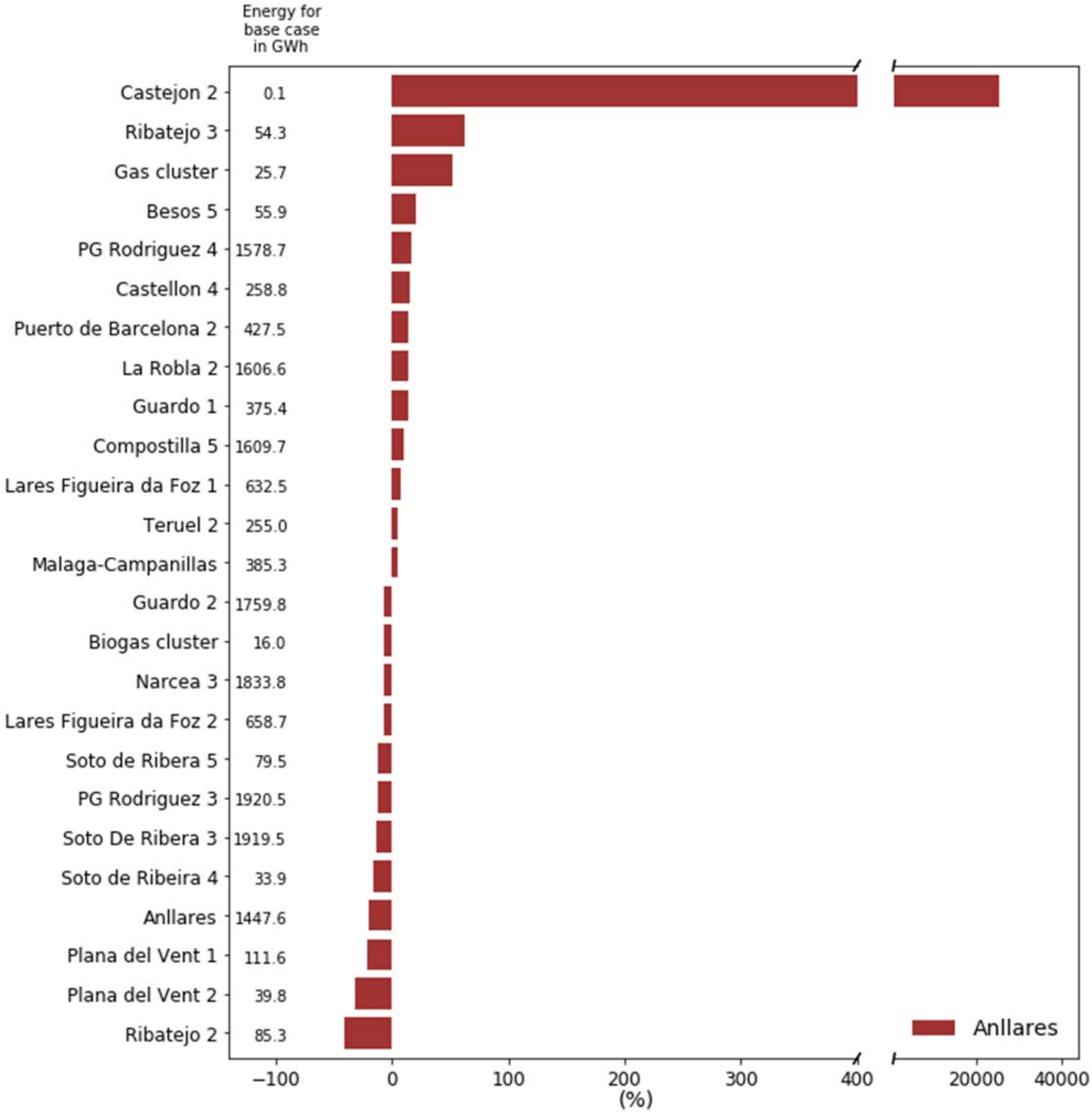
Source: JRC 2017.

Figure 52. Variation of annual energy production per power plant with a variation greater than 5 % for the '*Teruel* case' compared to the 'Base case'.



Source: JRC 2017.

Figure 53. Variation of annual energy production per power plant with a variation greater than 5 % for the '*Anllares* case' compared to the 'Base case'.



Source: JRC 2017.

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