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# The water-energy nexus and the implications for the flexibility of the Greek power system

*WATERFLEX project report*

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# Contents

## Abstract

The operation of the power systems is constrained by the availability of water resources, which are necessary for cooling thermal power plants and determine the generation of hydro reservoirs and run-of-river power plants. The interactions between the water and power systems have impacts on the quantity and quality of the water resources, thus affecting human uses and the environment.

The European power system has witnessed in the past several examples of the consequences of reduced availability of water, which range from monetary losses, to demand restrictions, or increased wear and tear of the power plants. The importance of these impacts, and the expectation that climate change will produce similar episodes in the future more often, raises several research questions relevant for policy making.

Some of these questions may be addressed by WATERFLEX, an exploratory research project carried out by units C7 (Knowledge for the Energy Union) and D2 (Water and Marine Resources) of the European Commission's Joint Research Centre (JRC). The main goal of WATERFLEX is to assess the potential of hydropower as a source of flexibility to the European power system, as well as analysing the Water-Energy nexus against the background of the EU initiatives towards a low-carbon energy system.

The method proposed in the WATERFLEX project for better representing and analysing the complex interdependencies between the power and water sectors consists of combining two of the modelling tools available at the JRC, the LISFLOOD hydrological model [1] and the Dispa-SET unit commitment and dispatch model [2], with a medium-term hydrothermal coordination model.

In order to test and validate the proposed approach described above, this document describes a case study carried out to analyse the implications of different hydrologic scenarios for the flexibility of the Greek power system.

# 1 Introduction

The operation of the power systems is constrained by the availability of water resources, which are necessary for cooling thermal power plants and determine the generation of hydro reservoirs and run-of-river power plants. The interactions between the water and power systems have impacts on the quantity and quality of the water resources, thus affecting human uses and the environment.

During the past decade there have been several examples of the consequences of reduced availability of water on the European power system. Table 1 shows some recent examples of thermal generation curtailments across Europe due to high river water temperatures or low river flows due to heat waves, which usually take place at periods of high power demand.

**Table 1.** Water impacts on European power systems [3], [4], [5].

| **Country** | **Reason** | **Impact** |
|---|---|---|
| France (2003) | Heat waves | Curtailing of nuclear power output<br>€300 million cost |
| France, Germany, Spain (2006) | High river water temperatures | Reduced nuclear generation |
| Poland (2015 and 2016) | Heat waves<br>Hydrological conditions of main rivers | Reduced coal power generation<br>Restrictions on industrial demand |

The consequences of this kind of events are monetary losses, demand restrictions, and increased wear and tear of the power plants. The importance of these impacts, and the expectation that climate change will produce similar episodes in the future more often, raises several research questions relevant for policy making:

— What is the water consumption resulting from the operation of the European power system under different scenarios (e.g. such as different power demand patterns, different shares of renewable energy sources, or availability of cooling towers)?

— What are the impacts of the water-related constraints (derived from the geographical and temporal availability and variability of water resources, reservoir management, and hydrothermal coordination) on the operation of the power system and on wholesale power prices?

— How are the emissions from thermal power plants affected by the operation of hydropower plants?

— What is the value of water availability?

— What level of flexibility is required by the power system?

This report describes a case study developed within the WATERFLEX project. WATERFLEX is an exploratory research project carried out by units C7 (Knowledge for the Energy Union) and D2 (Water and Marine Resources) of the European Commission's Joint Research Centre (JRC). The main goal of WATERFLEX is to assess the potential of hydropower as a source of flexibility to the European power system, as well as analysing the Water-Energy nexus against the background of the EU initiatives towards a low-carbon energy system.

Hydropower is a key cost-competitive resource for integrating the growing share of variable renewable energy sources (in particular wind and solar PV) into the European power system. Today, hydro reservoirs and pumped hydro storage are the most important technologies able of storing electric energy at a large scale, as well as a significant source of flexibility, since they can react fast to imbalances between power supply and demand.

Despite the assumed importance of hydropower for future energy systems, most of the power system models used today overlook water-related constraints and represent the availability and variability of hydrological resources in a very simplified way. However, hydrological-related "boundary conditions" (e.g. catchments, flows, irrigation uses, etc.) determine hydropower operations throughout the year, which in turn affect the operation of thermal power plants, and thus are crucial for estimating the needs for investment in flexible power generation resources. Moreover, the possible effects of exceptional hydrological years which are or can be representative for future climate are often not taken into account by power system models due to a lack of representation of the underlying principles.

In order to better represent and analyse the complex interdependencies between the power and the water sectors, the method proposed in the WATERFLEX project consists of combining two of the modelling tools available at the JRC, the LISFLOOD hydrological model [1] and the Dispa-SET unit commitment and dispatch model [2], with a medium-term hydrothermal coordination (MTHC) model, as illustrated in Figure 1. The interaction among the models is organised as follows:

— A series of assumptions, based upon historical data used by LISFLOOD, on constraints on hydropower plants, limitations of water withdrawal and consumption at thermal plants, and needs for cooling water uses, is fed into both the MTHC and the Dispa-SET models.

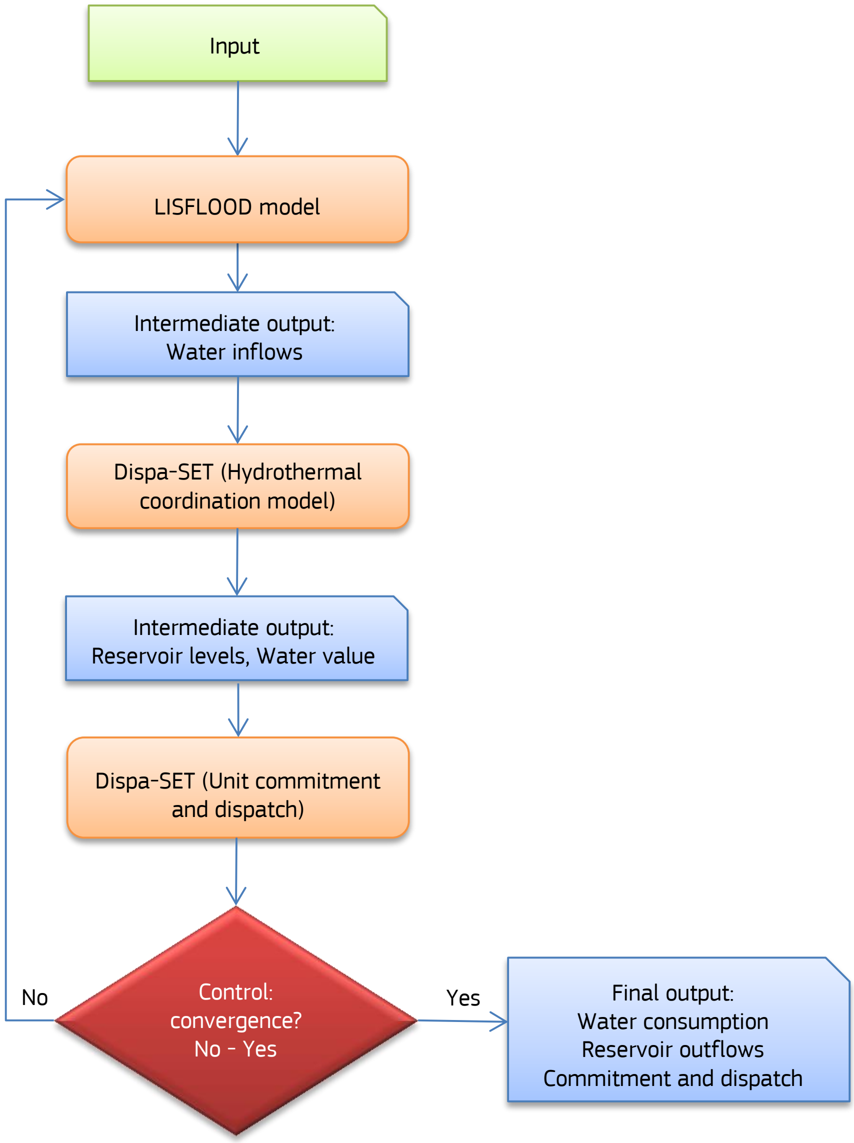
— The MTHC model establishes the operational limits of the hydropower plants (reservoir levels) during a certain period of time (usually one year, at time steps defined by the model user).

— The Dispa-SET model determines the scheduled operation and economics of the power plants of the system under analysis during the simulation period such as:

  - The amounts of water withdrawn and consumed for cooling thermal power plants.
  - The water releases from hydropower plants.
  - The dispatch and commitment decisions. As a by-product, emissions from thermal power plants can be estimated.

— The feasibility of the previous solution from the water system point of view is analysed. If the solution is not acceptable the assumptions are re-estimated and the process is reiterated under reaching a stable solution.

**Figure 1.** Interactions between LISFLOOD, MTHC, and Dispa-SET models




In order to test and validate the proposed approach described above (see [6]), this report describes a case study carried out to analyse the implications of different hydrologic scenarios for the flexibility of the Greek power system. Note that, for the analysis reported in this document, we discuss the results after the first run of the Dispa-SET model. Although the Greek power system is mainly thermal-dominant, there is a high share of hydropower with 21 hydropower plants including pumped hydro, reservoir, and run-of-river. This system is then suitable to thoroughly analyse the water-energy implications in an early stage of the proposed approach.

The Greek power system have been previously analysed in the technical literature from different perspectives, namely (i) policy [7], [8], [9], or (ii) mathematical [10], [11], [12]. From a policy perspective, Kaldellis *et al.* [7] and Kaldellis [8] are focused on examining the role of the small hydro power stations in the Greek power systems. The former performs both a techno-economic assessment and a sensitivity analysis of this growing technology in the mainland of Greece in order to highlight the profit of its investment. The latter summarizes the existing situation of small hydro power stations in Greece as well as their future economic or environmental impact. This existing situation of the Greek power system is compared on an international and European level in [9].

From a mathematical perspective, the MTHC problem has been addressed in several papers [10], [11], [12]. Baslis *et al.* [10] applied a yearly hydrothermal scheduling problem with hourly time resolution to the Greek power system. The mathematical model is formulated with mixed-integer linear programming and uncertainty on demand, water inflow, fuel price, and thermal unit forced unavailability is considered by using Monte Carlo simulations. However, the problem would become extremely hard to solve due to the large number of uncertainties and the time resolution of the problem. To make it tractable, the case study is solved by grid computing. The main results include medium-term outcomes such as the water value of the hydro power plants and short-term decisions on thermal power plants. Zoumas *et al.* [11] adopt a genetic algorithm to solve the MTHC problem. The results on the Greek power system are mainly focused on the performance of the algorithm in computational terms. Finally, Ourani *et al* [12] apply the so-called stochastic dual dynamic programming to the MTHC problem with uncertainty on water inflow; however the model of the thermal units is overly simplified. The performance of the algorithm is compared to the dual dynamic programming while the results for the Greek power system are discussed in terms of the total stored water volume and the shadow cost of the hydro power plants. Notwithstanding, none of the previous works have paid attention to the interaction water-energy in Greece, i.e., the implications of the water on the power system economics and operation, and the possible impact of the power system operation on the water sector.

The report is structured as follows. Section 2 describes the characteristics of the Greek power system, in particular its hydropower plants, as well as the scenarios analysed. Section 3 provides an overview of the results. Finally, section 4 concludes with a summary of the main lessons learnt from this analysis, a description of future activities, and some considerations regarding the technical and scientific challenges found in the project.

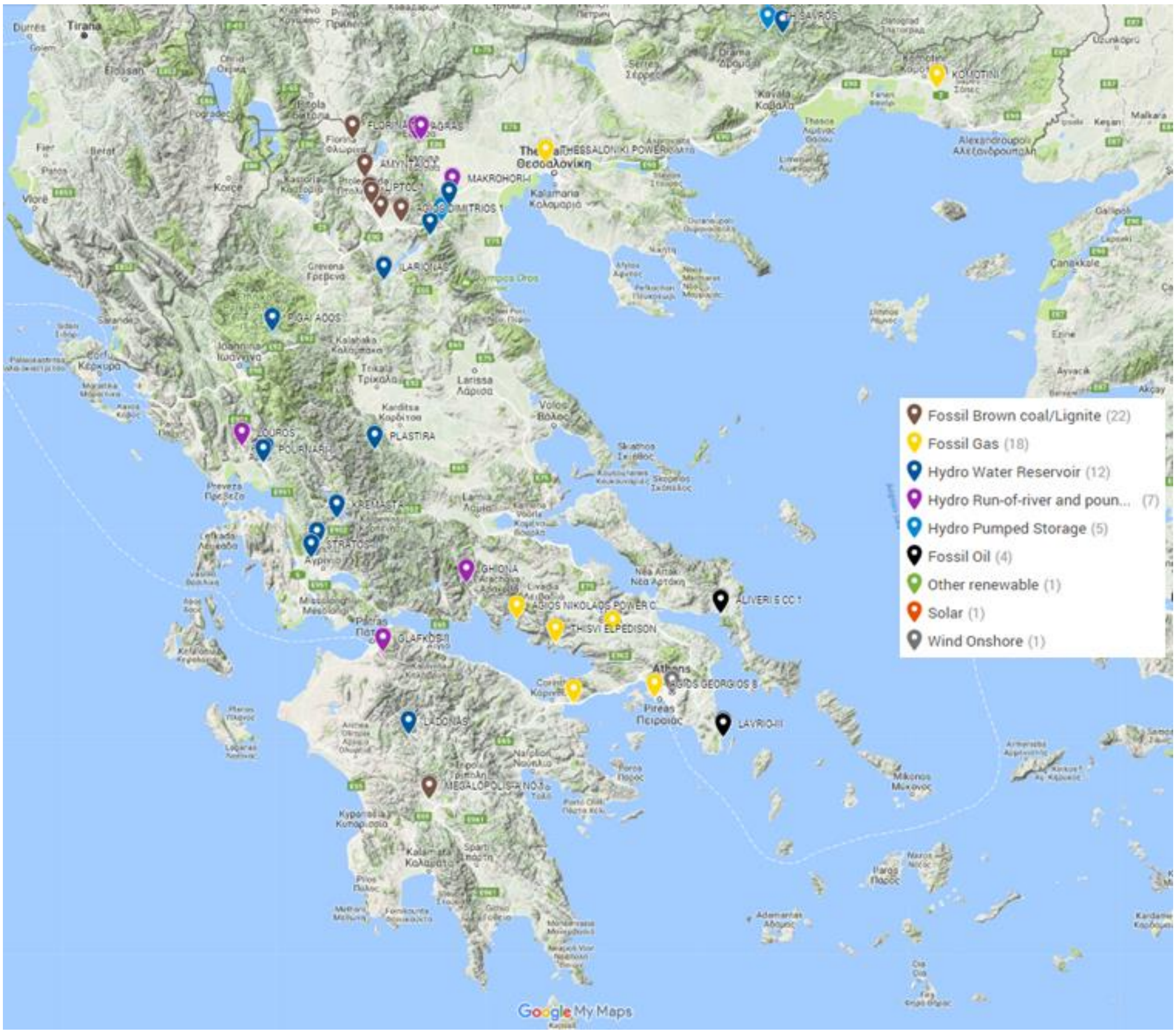
# 2 Characteristics of the Greek power system

In this section, the features of Greek power and hydrological systems are presented along with the energy and water time series collected. Note that we have used the names of the power plants as given in Platts' World Electric Power Plant Database throughout the rest of the report.

## 2.1 Power system: thermal plants

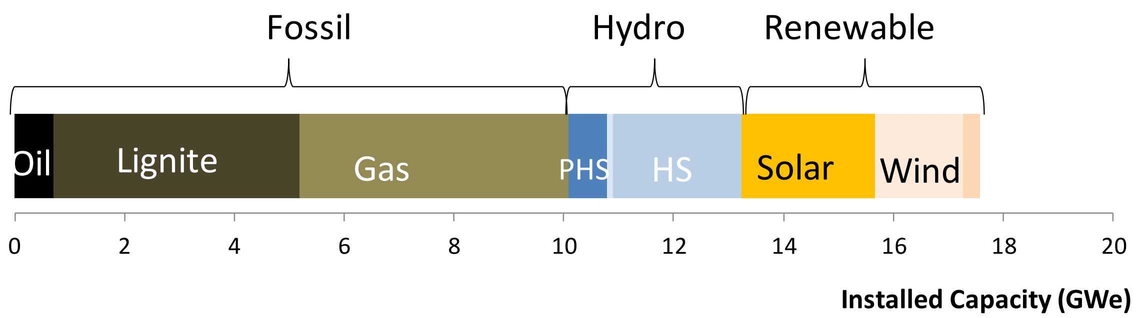
The Greek power system (mainland only) consists of 37 thermal and hydro power plants and several renewable facilities (solar and wind mainly). The location of the power plants accounted for in the case study is shown in Figure 2.

**Figure 2.** Location of the Greek power plants




According to Figure 3, the total installed capacity in 2015 amounted to 17625 MW [13], of which 10090 MW, 57% of the total, was thermal (4459 MW lignite, 4913 MW gas, 718 MW oil). Hydropower capacity amounted to 3149 MW, 18% of the total, of which 2347 MW corresponded to hydro water reservoirs, 693 MW to hydro pumped storage, and 109 MW to run-of-river plants. The remaining capacity, 4340 MW (25% of the total), was split into 2429 MW of solar capacity, 1613 MW of wind onshore mills, and 298 MW of other renewable generation technologies (biomass and geothermal).

**Figure 3.** Installed capacity in the Greek mainland power system




The main characteristics of the Greek thermal power plants are summarised in Annex 1. In this annex, it can be found the type of fuel and technology, the corresponding capacity, the minimum generation level in percentage with respect to the capacity, the variable costs, and the cooling technology used for each of the thermal generating units as well as their associated water consumption and withdrawal factors based on the average values collected in [14]. Some of these thermal power plants take water for cooling from underground aquifers, which may be a key factor for a water-energy analysis. As can be seen in Table 3, the water abstraction of fresh groundwater for cooling was 26.9 $Hm^3$, roughly a 30% of the total water abstracted for such purpose.

## 2.2 Power system: hydropower plants

The Greek hydropower system comprises seven river basins (Aliakmon, Nestos, Aheloos, Ladon, Tavropos, Aoos, and Arachthos), with the power stations listed in Table 6 of Annex 1. This table also provides the capacity of the power plant and the storage capacity of the associated reservoir. An overview of the most important characteristics of the reservoirs linked to hydroelectric plants is presented in Figure 4. The associated hydraulic topology of the river basins is depicted in Figure 5 and Figure 6, where it can be seen that the topology is quite simple for the Greek case. Note that the hydro power plants precluded in the figure are not interconnected.

**Figure 4.** Reservoirs associated with hydropower plants by size and head. Note that most important reservoirs are annotated.

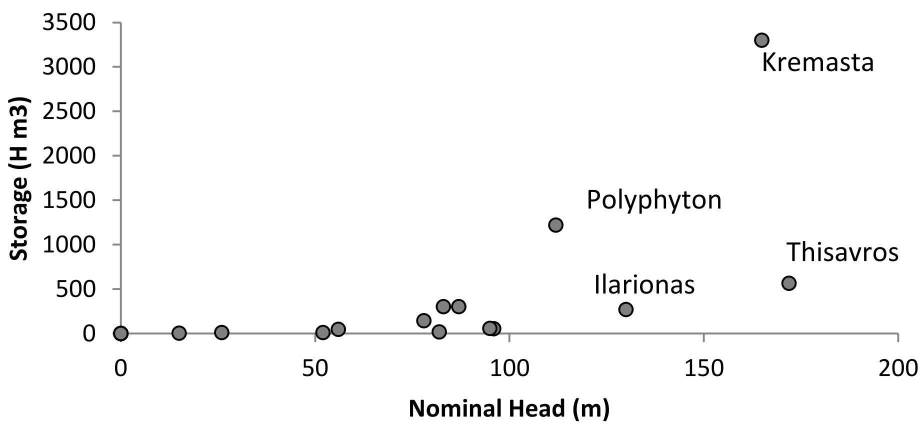


**Figure 5.** Network of hydroelectric plants plotted on a base map

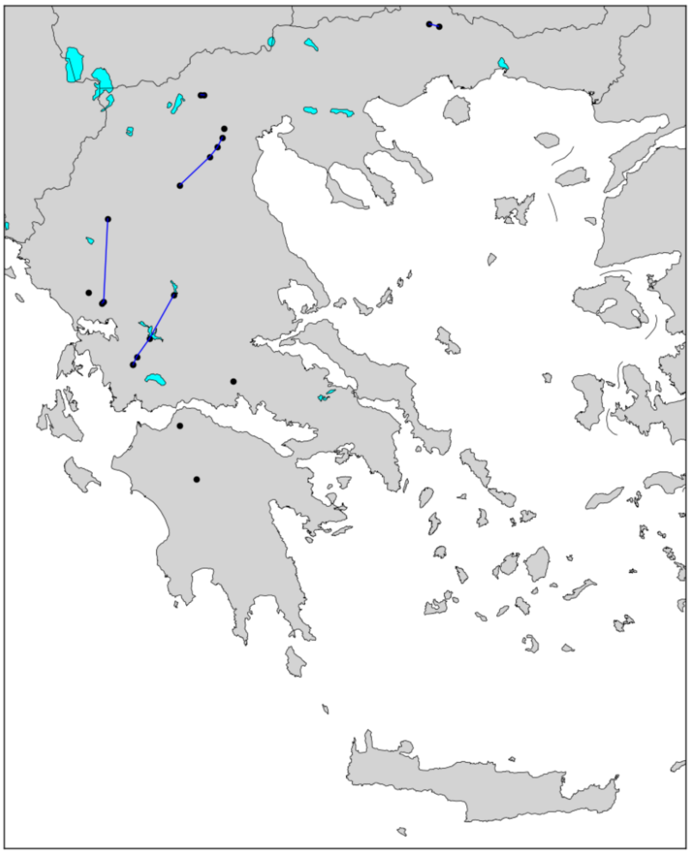
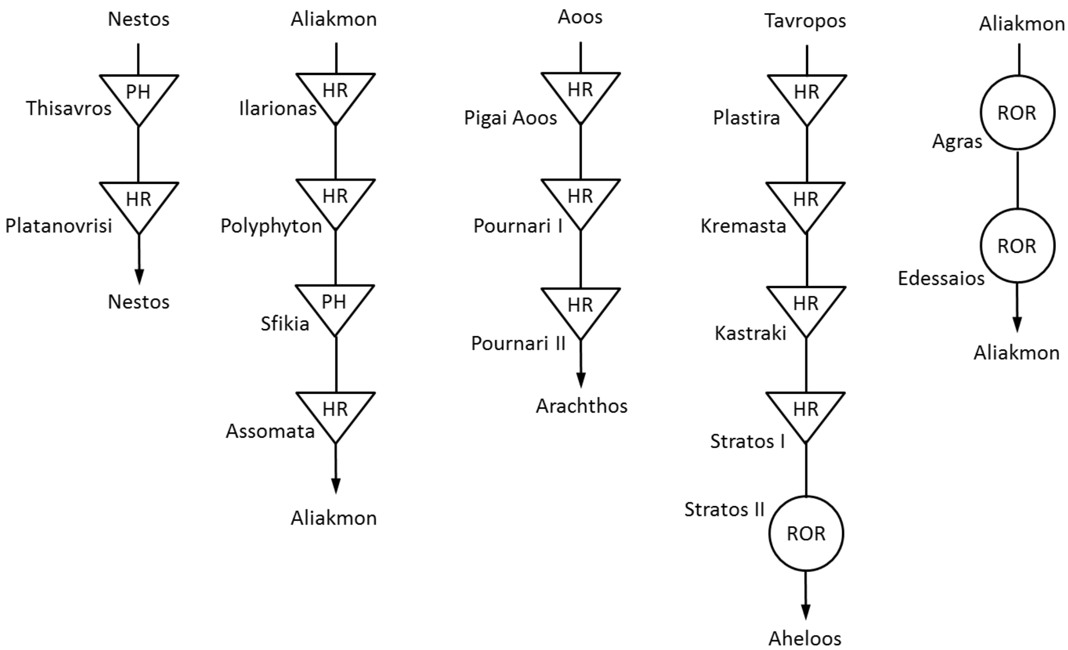


**Figure 6.** Hydraulic topology of the river basins (PH: pumped hydro, HR: hydro reservoir, ROR: run of river)



## 2.3 Power supply and demand time series

Historical time series were used for the creation of the scenarios. Detailed operational data were retrieved from ADMIE [15], the Greek independent power transmission operator, and ENTSOE [13].Figure 7 and Figure 8 illustrate the historical demand and hourly generation levels per power plant for the last ten years. Note that in the latter figure the darker the line the more a plant generated with respect to its corresponding maximum capacity.

**Figure 7.** Different demand load curves for a year (2004–2015). Mean, minimum and maximum load curves are emphasized

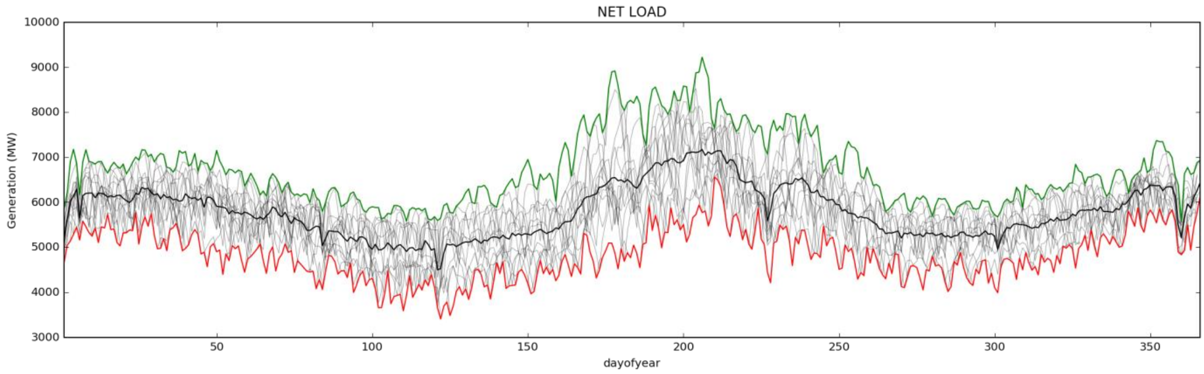
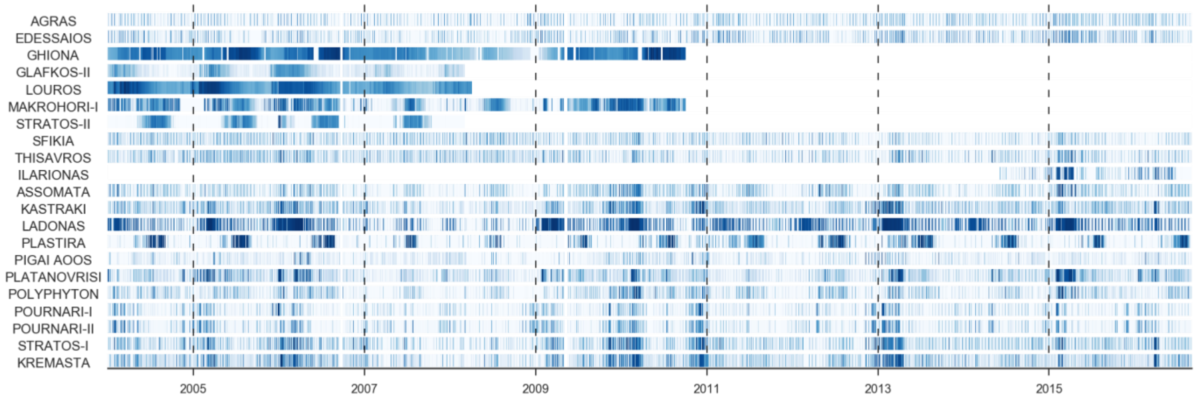


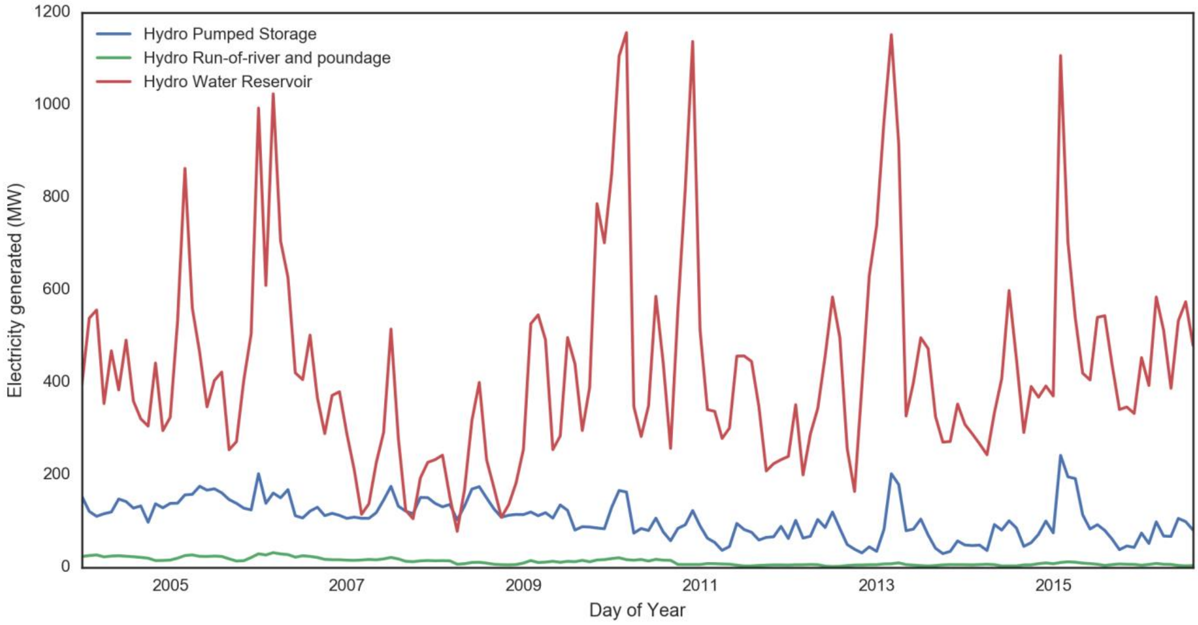

**Figure 8.** Dispatch plot of hourly generation of electricity by hydro power plant. The darker the line the more a plant generated related to its maximum capacity




The role of hydropower is also rather significant. Figure 9 provides the historical generation per type of hydro plant in the last 12 years. Hourly generation from water reservoirs reached a peak of 1979 MW, producing on average 511 MW. Pumped storage units produced a maximum of 687 MW, and 104 MW on average.

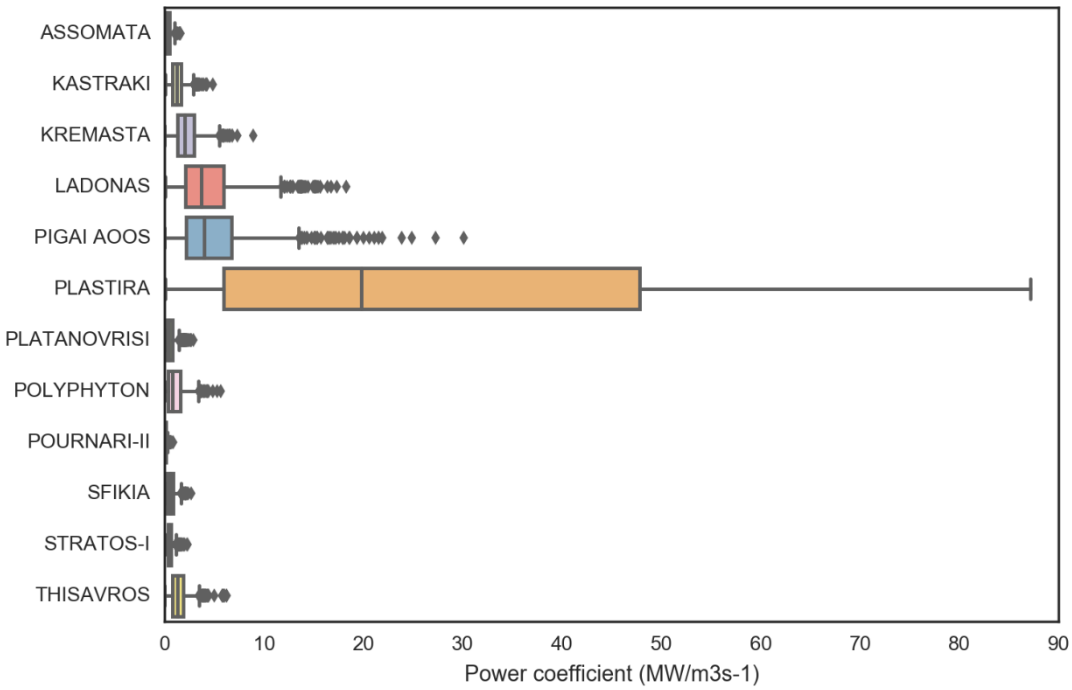
For the sake of analysis, we have used historical net inflows, i.e. inflows coming into one reservoir from the environment without considering upstream nodes of the hydrological network hydro plants. An annual distribution of these values for each hydro plant considered is shown in Annex 2.

**Figure 9.** Historical generation per type of hydro plant (2004–2016)




Based on historical values of discharges ($m^3s^{-1}$) [1] and generation (MW) [15] presented above, Figure 10 shows the distribution of power coefficients for all reservoir hydro power plants. Usually the power coefficient rises when the reservoir levels are higher as a higher pressure head leads to increased efficiency (more power produced per water discharged).

**Figure 10.** Historical power coefficients for all hydro plants



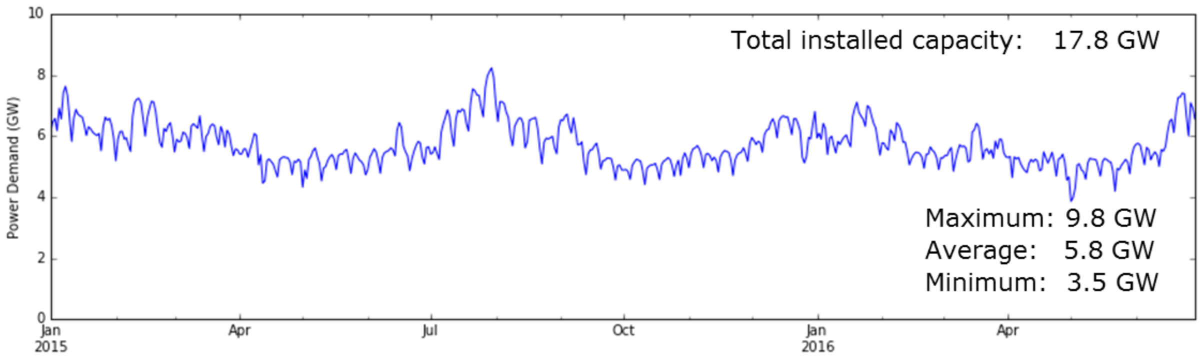
## 2.4 Data inputs for case study

The selected case study has the characteristics shown in the next subsections.

### 2.4.1 Demand

The demand time series of 2015 which are represented in Figure 11 were used for this case study. In 2015 the maximum load in the Greek system amounted to 9.74 GW, while the average was 5.81 GW, and the minimum 3.54 GW [13].

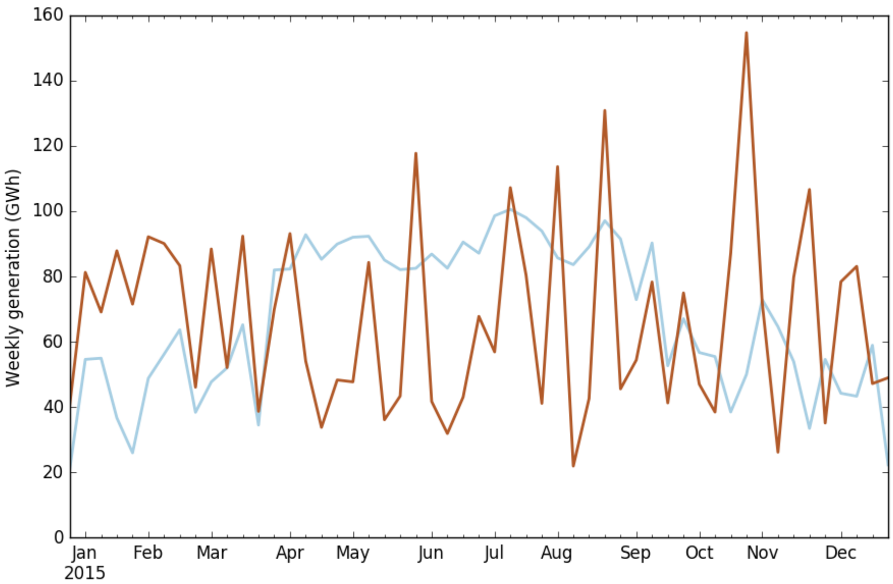
**Figure 11.** Daily demand in 2015 [13].




### 2.4.2 Renewable generation

Wind and solar capacity generated on average 404 MW and 409 MW respectively, but these technologies can also meet significant shares of the demand. The maximum solar hourly generation in 2015 reached 2062 MW while the wind peaked up to 1412 MW [13]. In Figure 12, the weekly generation for solar and wind onshore is represented. The maximum monthly production of solar generation is reached in July with 430.6 GWh whereas the maximum monthly wind generation can be found in August with 356.4 GWh.

**Figure 12.** Wind and solar generation **[15]**



### 2.4.3 Hydropower inflows

The case study is based on the analysis of three deterministic and representative scenarios (wet, average, and dry historical years). The scenarios are based on historical daily time series of water inflows provided by D2 from LISFLOOD [1] which was applied to the Greek system. This daily time series comprises 25 years spanning from 1990/01/01 till 2014/12/31. The wet, average, and dry historical scenarios correspond to years 2010, 1996, and 1992, respectively.

A Monte Carlo analysis was also conducted in order to understand the uncertainty of the reservoir levels. A simple periodic autoregressive PAR(1) model was used for the generation of the stochastic hydrological inflows based on their statistical characteristics (daily means and standard deviations) as presented in Figure 31. The detailed methodology is presented in [6].

# 3 Case study results and discussion

This section is devoted to analyse not only the consequences of water availability on the power system economics and operations, but also the repercussions of power system operation on the water availability for uses in other sectors.

## 3.1 Results from hydro thermal coordination problem

First, the interim results of the MTHC problem are presented in this section. The analysis is done using the demand of 2015 for three different hydrological years. Daily dispatch plots grouped by type of power plant, aggregate reservoir level, and weighted average cost of the electricity units are presented in Figures 13–15.

**Figure 13.** Interim results of MTHC model for average year

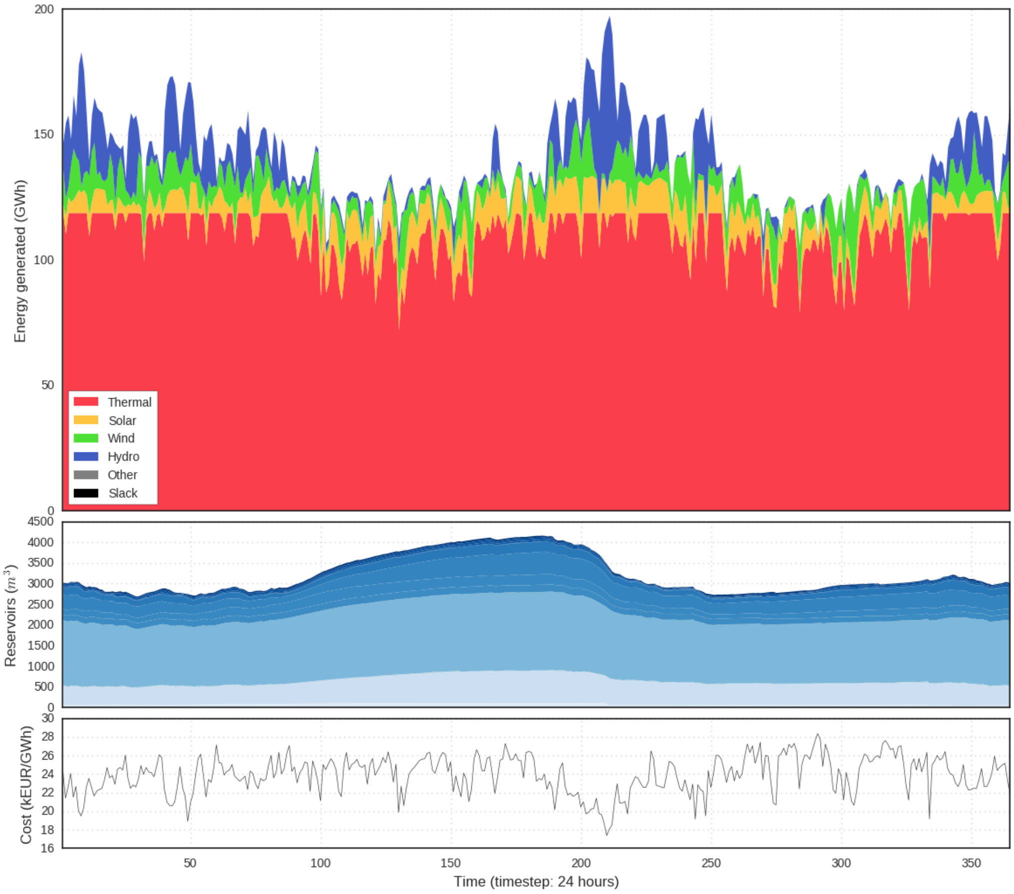


**Figure 14.** Interim results of MTHC model for dry year

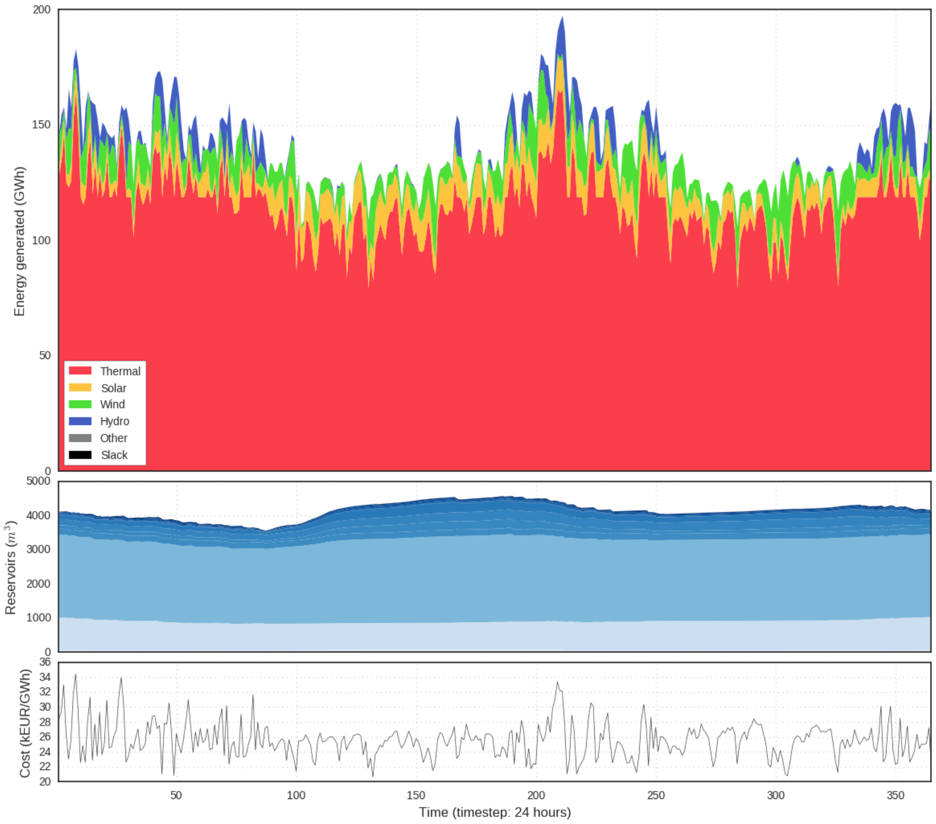
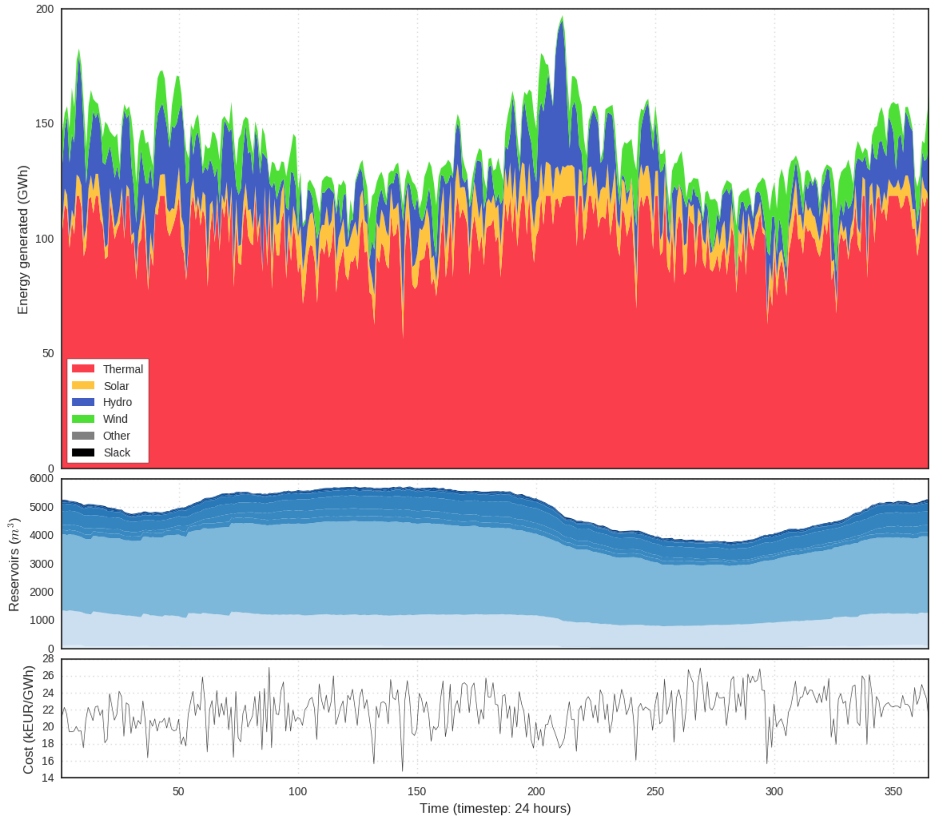



**Figure 15.** Interim results of MTHC model for wet year



A Monte Carlo simulation (50 iterations) was also conducted. Figure 16 shows the distribution of the objective values. The mean objective value is 1,077 k€ with a standard error of 68 k€.

**Figure 16.** Objective function solution values distribution of the Monte Carlo simulation

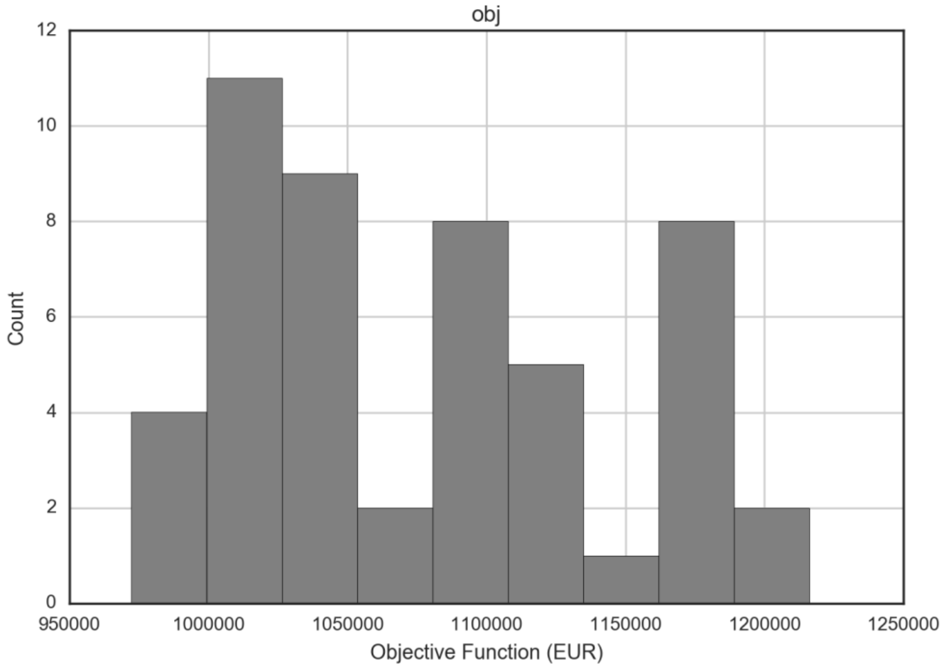
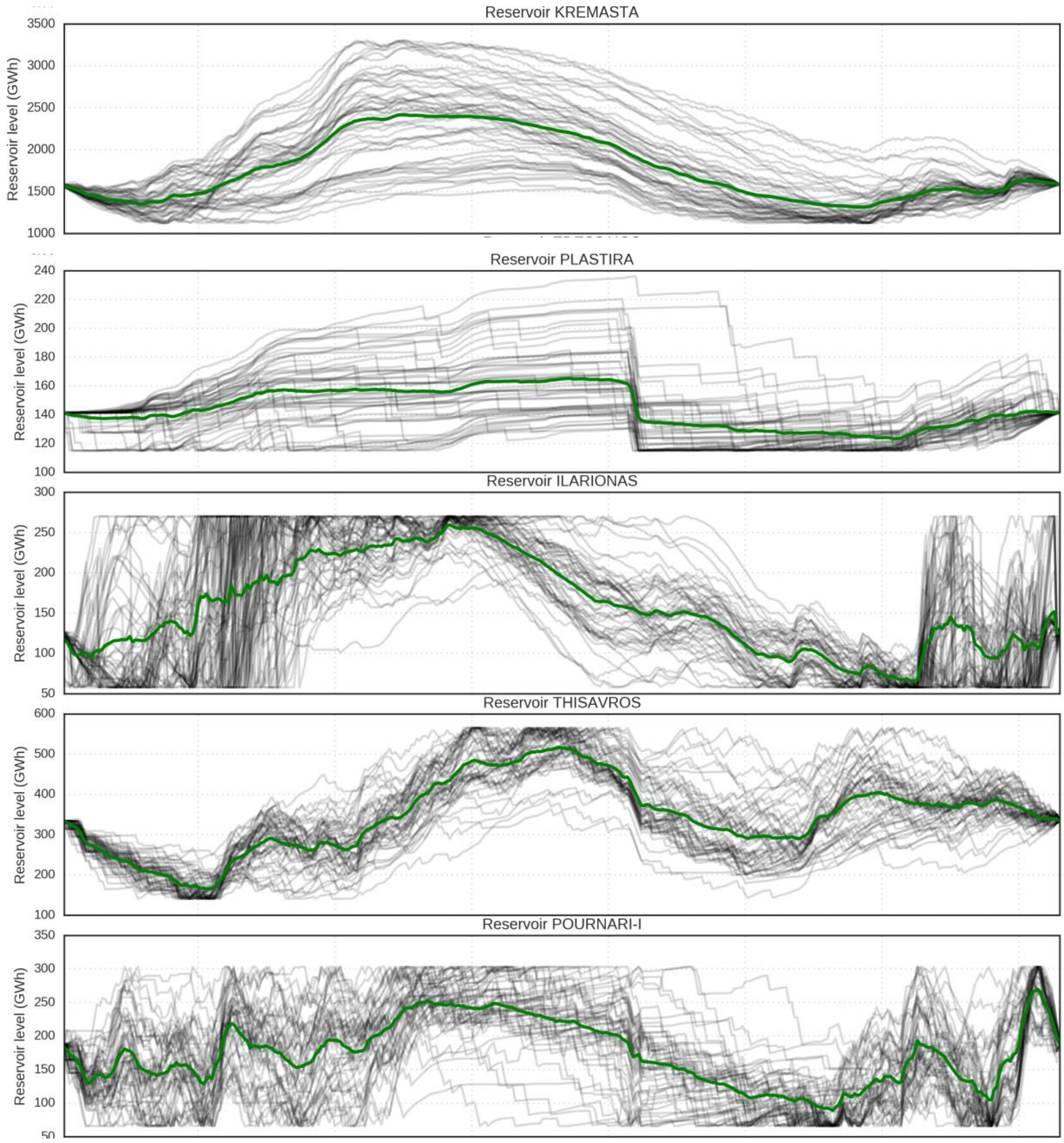



Figure 17 shows the results of the reservoir level for the biggest reservoirs. These curves can provide a nice overview of the expected values of each reservoir along with the uncertainty for each time step. The green line shows the expected value. It can be observed that there are periods of increased uncertainty, which are different per reservoir. In most cases the expected reservoir level is higher during the spring months.

**Figure 17.** Scenario generation from historical time series




Further analysis done in this report depends on the scenario analysis results and not on the Monte Carlo results.

## 3.2 Impact of water availability on the system economics and operations

The water availability affects the power system economics and operations as it can be observed in the following outcomes. We assume three historical scenarios for water inflows as explained in the previous section namely dry, average, and wet. Figure 18 shows the yearly generation costs resulting from Dispa-SET model for each historical scenario. As can be observed, the total generation costs including commitment, start-up, and shutdown costs decrease as the water availability increases in the system. Then, the costs increase 12.4% in the dry scenario compared to the cost in the wet scenario.

**Figure 18.** Annual generation cost per scenario

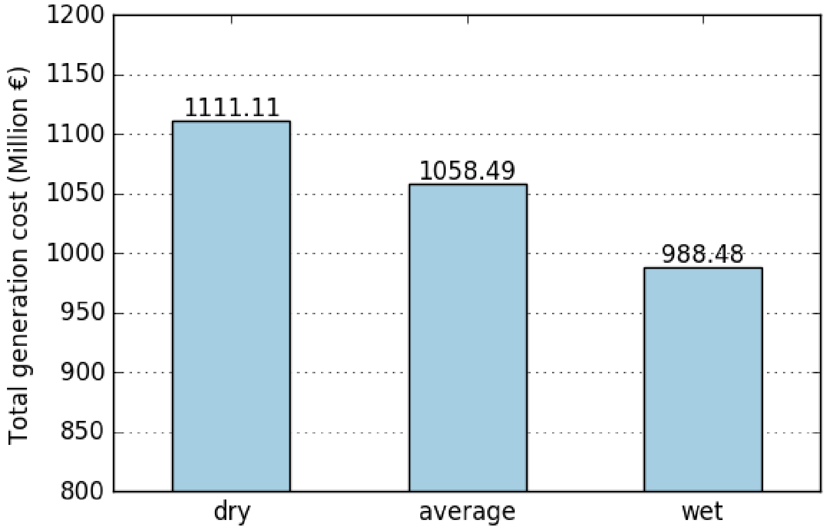


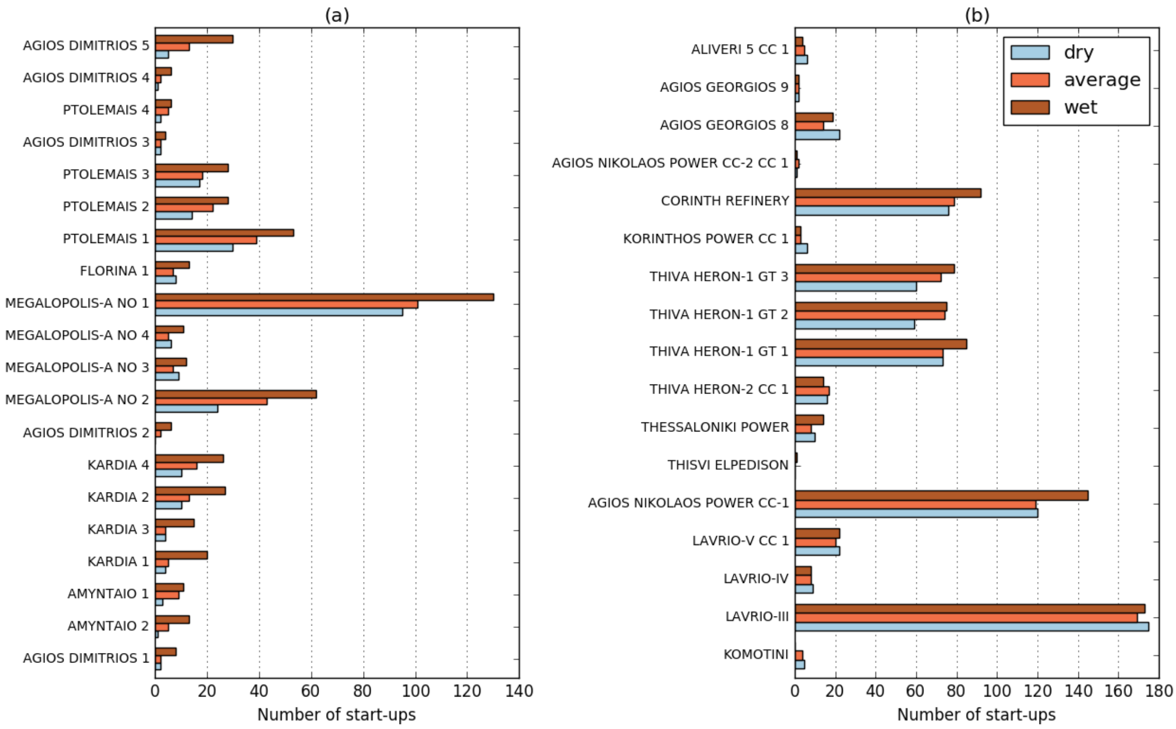

Table 2 lists different yearly metrics such as the average electricity cost, load shedding, and renewable curtailment. Although the wet scenario has lower average electricity cost or total load shedding compared to the average and dry scenarios, it may have a negative impact in other sectors different from the power sector due to floods or channel flow limitations. In turn, this could also have an impact on the analysed metrics.

In Table 2, we can also find the yearly number of commitments, start-ups, and shutdowns of all units, which are also influenced by the water availability in the system. The number of commitments decreases as the water availability increases since the hydropower production also increases. However, the total start-ups and shutdowns are lower for the dry and average scenarios than for the wet one because thermal units are committed less often in the latter scenario, thus reducing their number of cycles. Pollutant emissions are strongly related to the number of start-ups and shutdowns of thermal generators. Figure 19 itemizes the yearly number of start-ups per thermal generating unit and type. This figure gives an idea of the number of cycles of each thermal unit which consequently would affect to the pollutant emissions. The gas units "Lavrio-III" and "Agios Nikolaos Power CC-1" as well as the lignite unit "Megalopolis-A no 1" are the ones with more number of cycles per year. Also, the water availability could have a significant impact in the pollutant emissions. For instance, "Megalopolis-A no 1" has a greater number of start-ups in the wet scenario than in the other scenarios, i.e., the wet scenario leads to a 28.7% and 36.8% increase of the number of start-ups for that particular unit over the average and dry scenarios, respectively.

**Table 2.** Average electricity cost, load shedding, curtailment, total commitments, start-ups, and shutdowns per scenario.

| **Scenario** | **Dry** | **Average** | **Wet** |
|---|---|---|---|
| Average electricity cost (€/MWh) | 24.0 | 22.9 | 21.3 |
| Load shedding (GWh) | 1.7 | 1.3 | 1.3 |
| Curtailment (GWh) | 24 | 26 | 28 |
| Total commitments | 212,141 | 206,190 | 193,347 |
| Total start-ups | 1,725 | 1,727 | 1,936 |
| Total shutdowns | 1,738 | 1,734 | 1,946 |

**Figure 19.** Yearly number of start-ups for (a) lignite thermal units and (b) gas units




The water availability also affects the power dispatch of the generating units. For the sake of simplicity, we represent the annual energy production in TWh in Figure 20 instead of the hourly power dispatch. It can be clearly observed that the thermal power plants are still predominant in the Greek power system however hydro power is the second largest source of energy production. Notwithstanding, the water inflows have an obvious impact on the dispatch by reducing the share of "Fossil Brown coal/Lignite" production from 73.1% for the dry scenario to 66.4% for the wet scenario. As a consequence, the hydro energy production rate for the wet scenario (16.6%) has doubled the energy production rate for the dry scenario (8.8%). The increase of thermal energy production for the dry scenario could have severe consequences in the water-energy nexus due to the water needed for cooling. This impact is thoroughly analysed in subsection 3.3. In contrast, the wet scenario could lead to suboptimal solutions in other sectors, i.e., in the agricultural sector, or environmental consequences due to the large amounts of discharged water.

**Figure 20.** Annual energy production per type and scenario. Note that "Other" refers to generation of other renewables apart from wind and solar generation

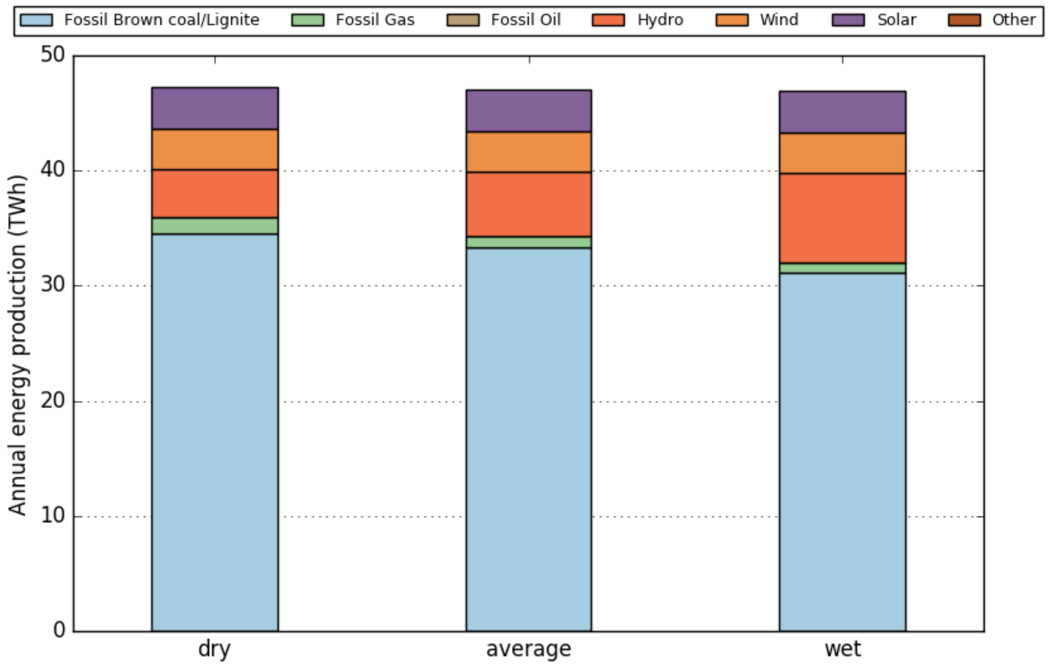
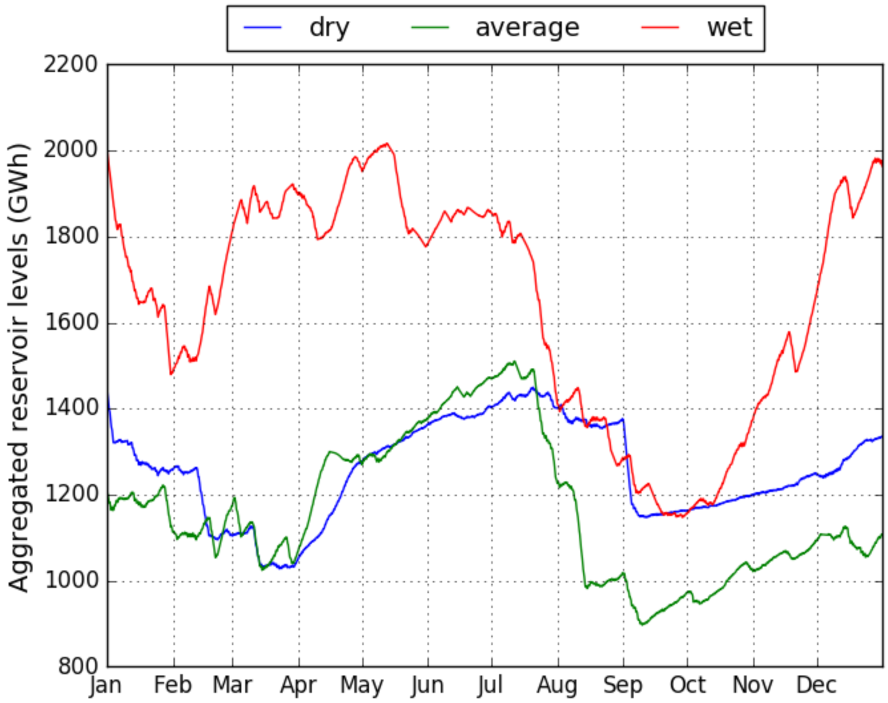


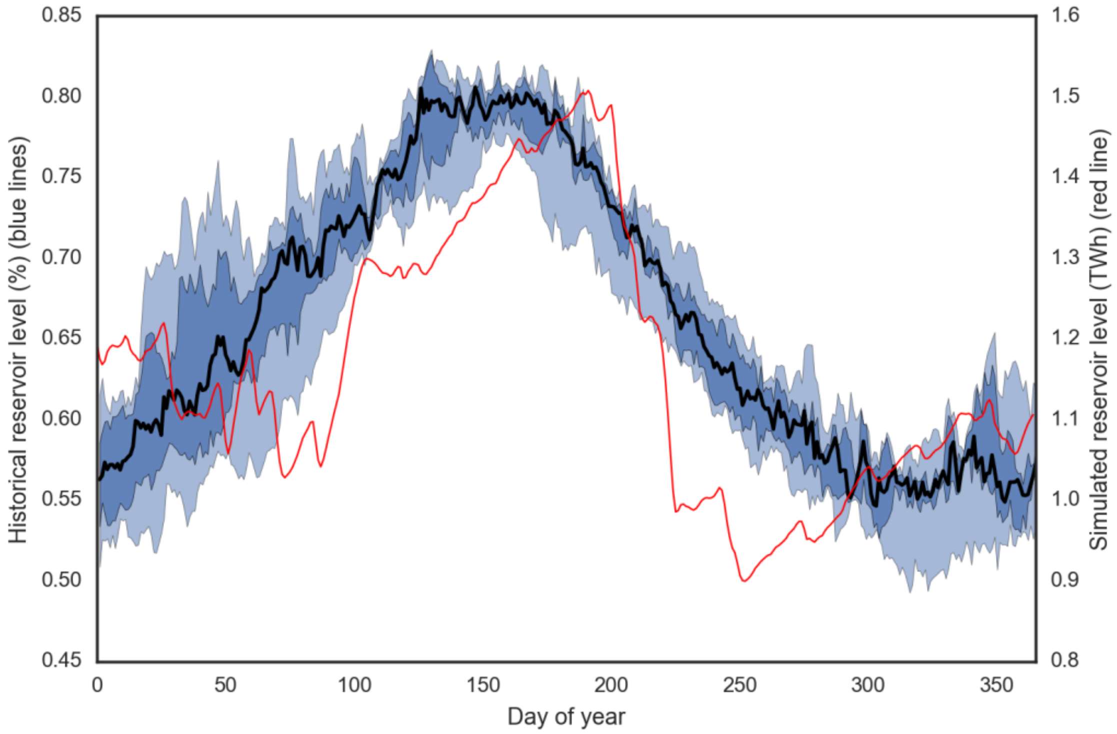

Figure 21 depicts the aggregated hourly reservoir levels in energy units. For this case study, the pattern of this output is similar for each scenario but maximum and minimum peaks are attained in different periods. The maximum reservoir level (2.02 TWh) is found in May for the wet scenario whereas the peak is found in July for the average (1.51 TWh) and dry (1.45 TWh) scenarios. Regarding the minimum reservoir level, it is reached around September for the average and wet scenarios (0.90 and 1.15 TWh respectively) and around March for the dry scenario (1.03 TWh). During the last months of the year, the reservoir levels for the dry scenario are greater than those for the average scenario since the selection of the scenarios is based on the water inflows rather than filling rates. However, one can observe a linear relationship between the temporal variability of the reservoir level (difference between the maximum and minimum levels) throughout the year and the availability of water (scenario). This temporal variability is equal to 0.42, 0.61, and 0.87 TWh for the dry, average, and wet scenarios.

**Figure 21.** Aggregated hourly reservoir levels in energy units per scenario




Historical time series of storage were also used in order to see how they compare with the results of the optimization. While we do not expect to see the same behaviour for various reasons (unknown environmental constraints, market regulations, technical outages, operational decisions, etc.) it is a good indication of how close our analysis is to the reality. Figure 22 compares historical storage levels of the last 5 years with the ones simulated by the average scenario. It can be seen that the same seasonal pattern is followed where there is high storage of energy during spring and summer months and lower storage levels during fall and winter.

**Figure 22.** Comparison of historical time series (left axis) with simulated results for average scenario (right axis, red line)




### 3.2.1 Water value of hydropower plants

One key metric that should be considered in the interactions between power and energy is the water value. The water value of each hydropower plant at each period is mathematically defined as the absolute value of the derivative of the generation cost with respect to the water inflows [16]. In other words, the water value is the absolute value of the dual variable associated with the water balance equation in the MTHC problem. These values would provide the right economic signal in the short-term operation of the power system for scheduling hydro power, for instance in the unit commitment problem. In this report, we still do not consider the water value within the short-term operation of the power system.

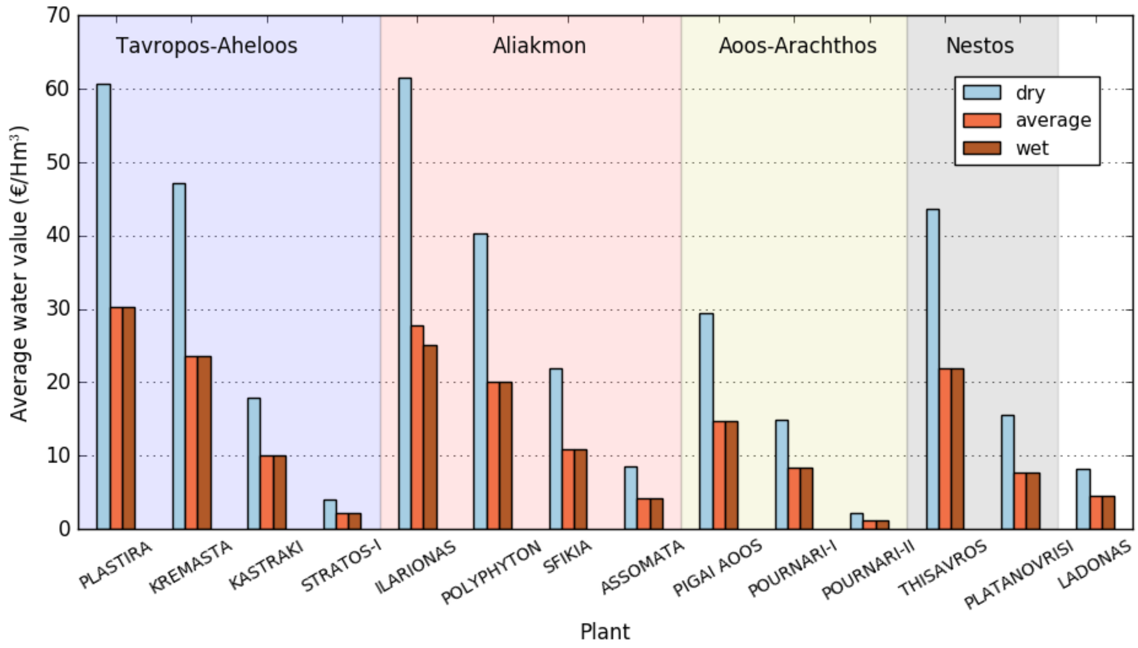
Figure 23 represents, for each scenario, the average daily water value in €/Hm$^3$ for all the hydropower plants except from the run-of-river power plants, which have a negligible water value. In this figure, we can also identify the water values for the hydro power plants per cascade and, within each cascade, the corresponding hydro power plants are in an upstream-downstream order. Several interesting remarks should be highlighted:

— As can be seen, the water value in the dry scenario is usually higher than in any other scenario. This means that the thermal power plants with marginal costs below those values would have priority to be committed. There is only one difference between the water values in the average and wet scenarios and it corresponds with the one associated with "Ilarionas".

— It is also important to point out that the size of the reservoir is also related to the water value. We can easily see that the highest values can be found for "Plastira", "Kremasta", "Ilarionas", "Thisavros", "Platanovrisi", and which correspond to the biggest reservoirs.

— As similarly observed in [11], the hydraulic topology has a drastic impact on the water value of the hydro power plants. Irrespective of the scenario, the downstream hydro power plants of a specific cascade have a smaller water value, which is an indication of the economic potential of the upstream hydro power plants compared to those downstream.

**Figure 23.** Average daily water value per scenario. Note that the background colour is associated with each river basin or cascade and the hydro plants are in an upstream-downstream order




## 3.3 Impact of power system operations on water availability

The power system operations also impact on the water availability for other sectors due to the cooling of thermal power plants. As can be seen in Table 3, the gross water abstraction in Greece in 2007 (last year available in EUROSTAT)([1]) from the fresh surface and groundwater was 9,538.6 $Hm^3$ and the annual freshwater abstraction for production of electricity (cooling) was 100.4 $Hm^3$. This water abstraction represents around 1% of the total gross abstraction, which is seemingly negligible. However, it represents around an eighth of the water abstraction for public water supply, or approximately one quarter of the water consumed in Athens in 2007 [17]. Table 3 also itemizes the shares of water abstraction by source and sector per fresh surface water and fresh groundwater. We can observe that roughly the 30% of the water abstraction for production of electricity (cooling) comes from fresh groundwater, whereas the 70% corresponds to the fresh surface water.

([1]) EUROSTAT: http://ec.europa.eu/eurostat/web/products-datasets/-/env_wat_abs

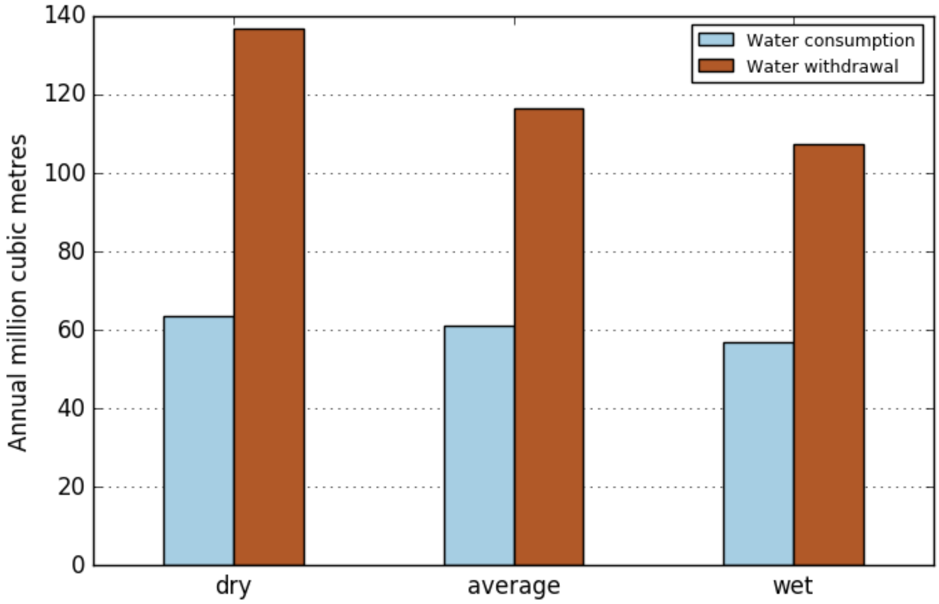
**Table 3.** Annual freshwater abstraction by source and sector in Greece ($Hm^3$).

| Sector | Fresh surface and groundwater | Fresh surface water | Fresh groundwater |
|---|---|---|---|
| Total gross abstraction | 9,538.6 | 5,820.5 | 3,651.1 |
| Water abstraction for public water supply | 846.2 | 648.3 | 198 |
| Water abstraction for agriculture | 8,457.9 | 5,074.8 | 3,383.2 |
| Water abstraction for agriculture - irrigation | 8,457.9 | 5,074.8 | 3,383.2 |
| Water abstraction for agriculture - aquaculture | - | - | - |
| Water abstraction for mining and quarrying | 67 | 24 | 43 |
| Water abstraction for manufacturing industry | - | - | - |
| Water abstraction for manufacturing industry - cooling | - | - | - |
| Water abstraction for production of electricity - cooling | 100.4 | 73.5 | 26.9 |
| Water abstraction for construction and other industriel activities | - | - | - |
| Water abstraction for services | - | - | - |
| Water abstraction for private households | - | - | - |
| Water abstraction - net | 9,440.1 | - | - |
| Water returned without use | 31.5 | - | - |

### 3.3.1 Water consumption and withdrawal

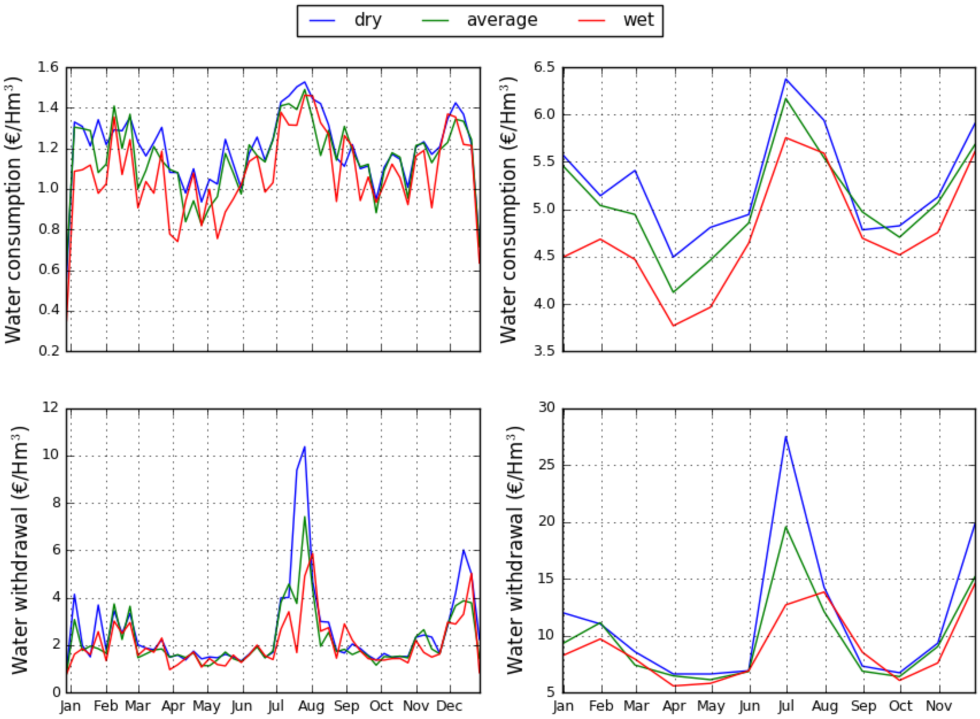
Figure 24 shows that the operation of the power system regardless of the scenario requires significant amounts of water withdrawal if it is compared to the water abstraction for the same purpose in Greece in 2007 (see Table 3). The water withdrawal drastically increases to 27.4% for the dry scenario compared to the annual withdrawal for the wet scenario. However, the change in water consumption is less pronounced when shifted to a dry scenario. Finally, the returned water of the corresponding total withdrawal is equal to 53.7%, 47.5%, and 47.0% for the dry, average, and wet scenarios, respectively, which can greatly impact on the thermal pollution (for instance, rising of water temperatures).

**Figure 24.** Annual aggregated water withdrawal and consumption



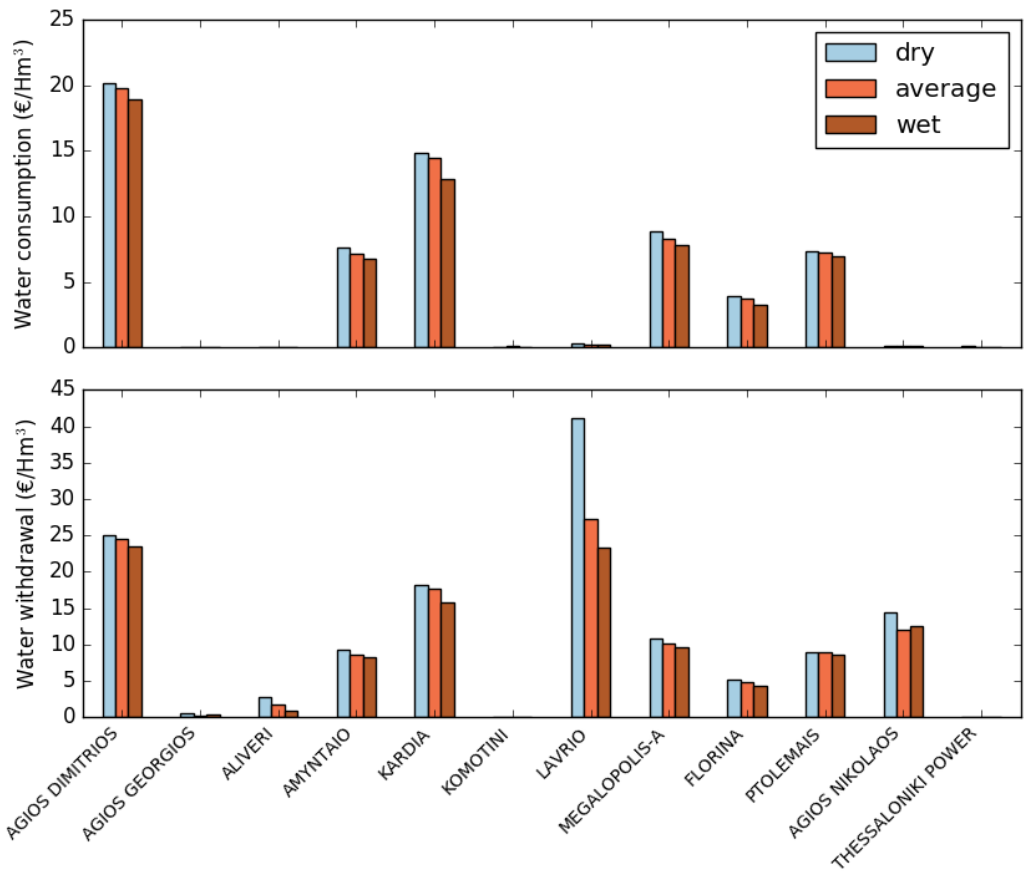

The proposed method also allows determining the most critical periods in each scenario. The itemized water consumption and withdrawal per week and month are respectively shown in the left-hand side and right-hand side of Figure 25 for each scenario. These values allow us to clearly identify that the peak withdrawal occurs around summer in Greece. Specifically, the monthly values give us an idea on how the water availability affects to the water consumption and withdrawal as similarly shown in the previous figure. The most critical periods take place usually around July and towards the end of the year. The maximum monthly water consumptions are around 6 $Hm^3$ (roughly 10% of the annual water consumption) regardless of the scenario, whereas the minimum monthly water consumption occurs in April and amounts to 5.6 $Hm^3$ for the wet scenario. Regarding water withdrawal, the maximum monthly peak takes place on July with 20.1% and 16.8% of the annual water withdrawal for the dry and average scenarios, and on December with 13.6% of the corresponding annual withdrawal for the wet scenario.

**Figure 25.** Aggregated weekly (on the left) and monthly (on the right) water consumptions and withdrawals per scenario. Note that y-axis limits are different in each plot




As water availability decreases (from wet to average to dry) the water needed for cooling of thermal power stations increases while hydropower output decreases as can be seen in Figure 20. When the water availability is reduced, thermal generation (and the corresponding greenhouse gas emissions) increases (together with the water needs for cooling) in order to offset the decrease in hydropower output and meet the power demand (usually high during summer time in Greece). As a consequence, the annual water consumption and withdrawal increase for the dry scenario, as can be observed in Figure 26, which summarizes the annual consumptions and withdrawals per thermal power plant. Those thermal power plants (e.g., "Lavrio" or "Agios Nikolaos") with once-through technologies for cooling are characterized by large water withdrawals compared to water consumptions which in turn lead to more thermal pollution.

**Figure 26.** Annual water consumption and withdrawal per thermal power plant and scenario




### 3.3.2 Water stress index

In certain moments (usually during dry years) the water system may become so stressed that there is no water available for cooling specific thermal plants, which therefore need to be shut down until the water conditions improve. The water stress index is calculated as the "Water Withdrawn/Water Runoff" ratio at the site of the power plant. The index varies between 0 (no stress at all since no water is withdrawn) and 1 (all the water available is used for cooling). As an example, Figure 27 provides the water stress index for the "Megalopolis" power plant based on historical power production values and the water available on that specific site computed with the LISFLOOD model [1]. There are certain periods in which this index is higher. Extreme conditions such as future scenarios of climate change could exacerbate this water stress index. For the sake of completeness, Annex 3 provides the historical water stress index for the rest of thermal power plants.

**Figure 27.** Historical water stress index for the Megalopolis power plant

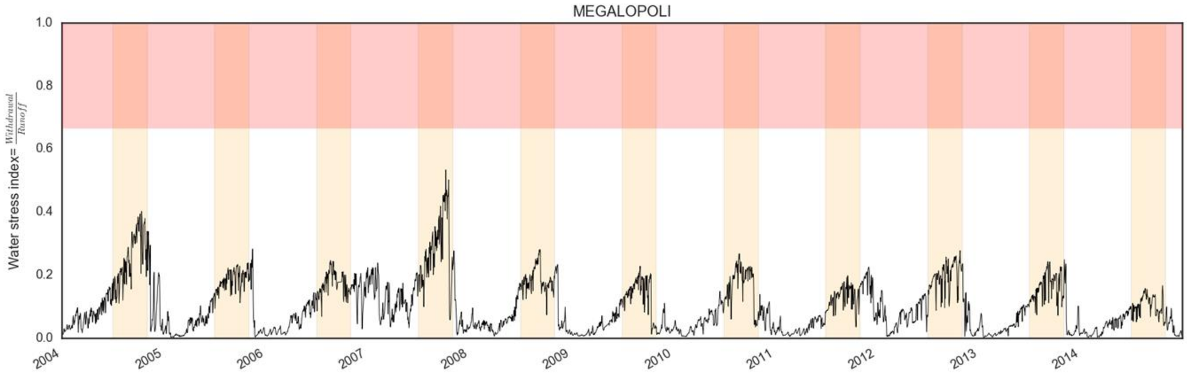



Figure 28 provides the daily water stress index for each of the thermal power plants of the Greek power system located close to a river and for each scenario. It can be observed that the water stress usually is higher for the dry scenario regardless of the thermal power plant. The maximum water stress index can be found around October for "Agios Dimitrios" reaching almost 1, which means that most of the water available in that period is used for cooling that specific thermal power plant, and thus its use for other purposes could be very limited. From June onwards the water stress increases in all the power plants. The plants most affected by the lack of water would be "Agios Dimitrios", "Megalopolis-A" and "Kardia". The average values of the water stress index per scenario are represented in Figure 29. In this figure we can see that in the dry scenario the water stress is not only crucial from June onwards but also at the first semester of the year.

**Figure 28.** Daily water stress index for each thermal power station under dry (a), average (b), and wet (c) scenarios

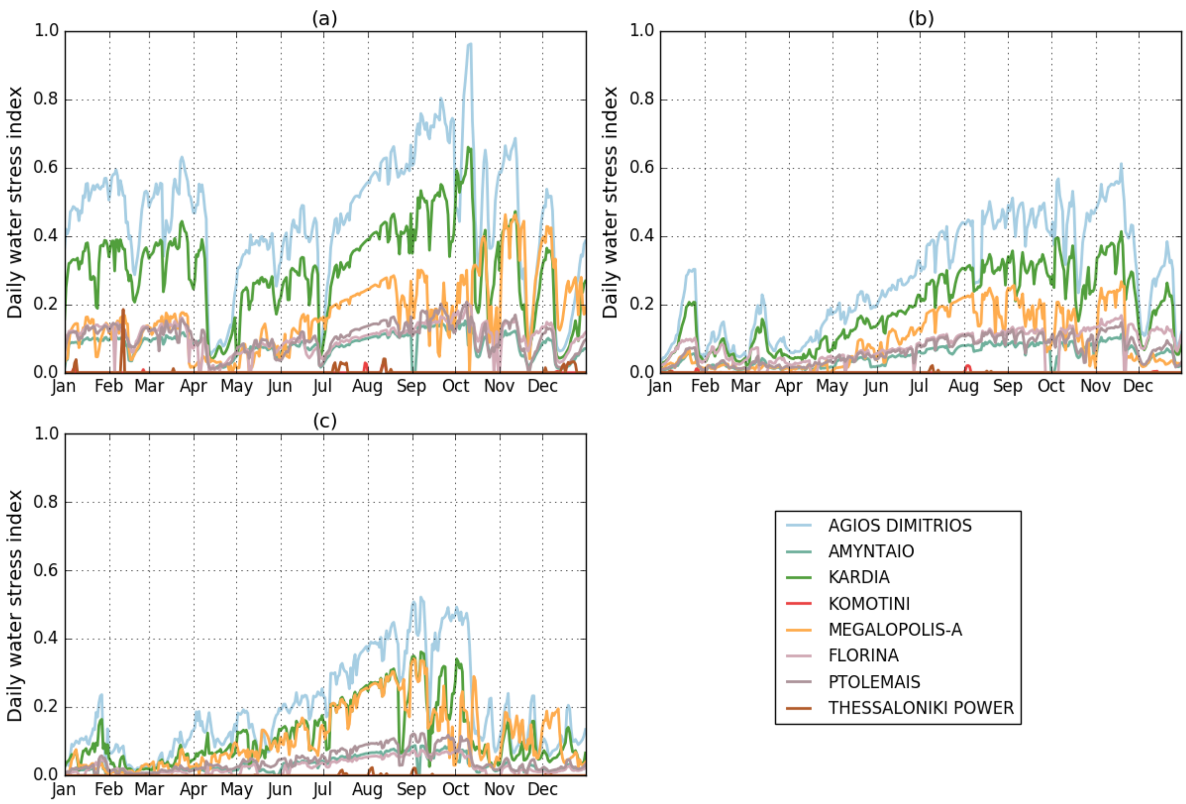
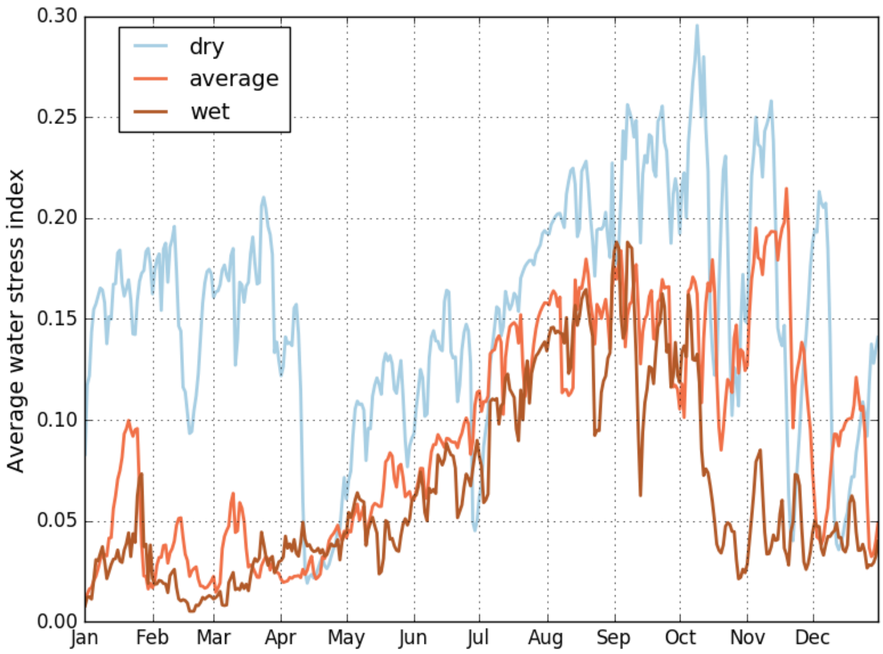
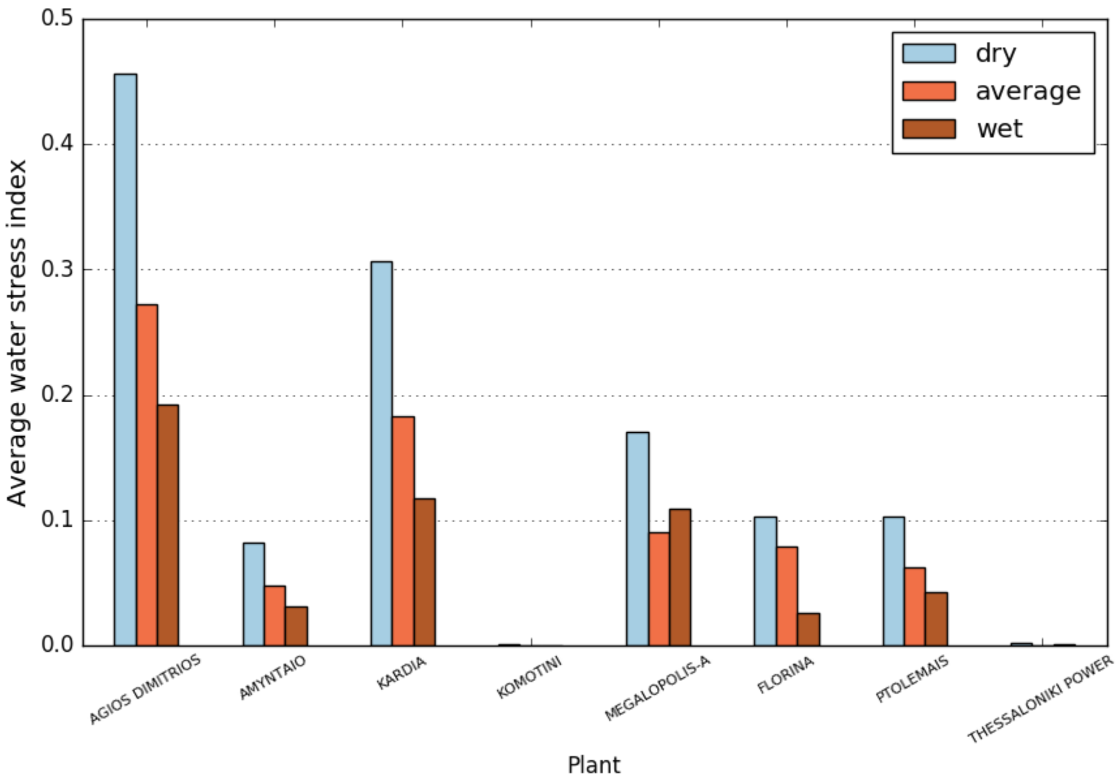


**Figure 29.** Overall water stress index for each scenario




Based on the water stress index, thermal power plants prone to be stressed under different climate scenarios can be easily identified. In Figure 30, the average values of this index per power plant are depicted for each scenario. From this figure, the effect of the lack of water is clearly seen for each thermal plant being more pronounced for "Agios Dimitrios" and "Kardia".

**Figure 30.** Annual average water stress index for each thermal power plant



# 4 Conclusions

The main conclusion of the case study described in this report is that the method proposed within the WATERFLEX project is able to produce a sound and detailed analysis of the interactions between the water and power systems based on a scenario-based study, as shown in section 3. This section analyses not only the implications of water on power system economics and operations but also the consequences of power system operations on water availability under three historical scenarios (dry, average, and wet).

For the Greek power system presented in this report, the hydro energy production rate for the dry scenario is half of that for the wet scenario and the hydropower reservoirs are less prone to perform temporal arbitrage in the dry scenario. As a consequence, the annual generation costs could increase by 12.4% in the dry scenario with respect to the wet scenario. However, the wet scenario could lead to negative environmental implications because the number of start-ups increases around 30% over that in the drier scenarios. In contrast, the power operation of the Greek system a drastic increase around 27% of the water withdrawal in the dry scenario compared to the wet scenario. This increase could impact on the water use for other purposes such as agricultural or human use. Also, this method allows for identifying the locations and time periods that may be stressed in a dry hydrological year which may be useful to adopt preventive measures rather than corrective ones.

Some of the activities to be carried out in the second part of the WATERFLEX project (during 2017) include:

— The precise modelling of water-related constraints in Dispa-SET.

— The coupling of models with different degrees of complexity (the stochastic mid-term hydrothermal module with the unit commitment and dispatch module of Dispa-SET, interactions between LISFLOOD and Dispa-SET).

— The coupling of datasets, including the linkage between physical reservoirs and water dams, the collection and verification of dam features (head, storage sizes, etc.), and the validation with stored and discharged energy.

— Discovering a methodology to utilize available historical time series of electricity generation, hydrological inflows and reservoir levels

— Definition of future climate and energy system scenarios to be done in liaise with other modelling activities

— European-wide analyses, in particular the Alpine region, Scandinavia, the Iberian Peninsula, and the Western Balkans.

These activities will require facing several technical and scientific challenges concerning:

— The modelling of the stochastic mid-term hydrothermal coordination problem.

— Striking a right balance between accuracy and complexity of water-related constraints such as the:

  - Cooling of thermal power plants.
  - Water balances and topology of the water network.
  - Technical features of the reservoirs (discharge/spillages bounds and ramp rates)
  - Treatment of uncertainty.

— Other choices that have a significant impact on the computational complexity and the data requirements, such as the most convenient temporal and spatial resolution of the models, how to cluster power plants, or the definition of policy-relevant scenarios.

— The complexities associated to the linkage of records from different datasets.

— The sheer availability of data

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## List of figures

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# ANNEX

## Annex 1: Techno-economic features

The former table lists the type of fuel and technology, the corresponding capacity, the minimum generation level in percentage with respect to the capacity, and the variable costs. The latter table lists the cooling technology used for each of the thermal generating units and the associated water consumption and withdrawal factors based on the average values collected in [14].

**Table 4.** Techno-economic features of the Greek thermal power plants I.

| Power plant | Fuel | Technology(*) | Capacity (MW) | Minimum generation level (%) | Variable costs (€/MWh) |
|---|---|---|---|---|---|
| AGIOS DIMITRIOS 1 | Lignite | STUR | 274 | 50 | 60 |
| AGIOS DIMITRIOS 2 | Lignite | STUR | 274 | 50 | 60 |
| AGIOS DIMITRIOS 3 | Lignite | STUR | 283 | 50 | 60 |
| AGIOS DIMITRIOS 4 | Lignite | STUR | 283 | 50 | 60 |
| AGIOS DIMITRIOS 5 | Lignite | STUR | 342 | 50 | 60 |
| AMYNTAIO 1 | Lignite | STUR | 273 | 50 | 60 |
| AMYNTAIO 2 | Lignite | STUR | 273 | 50 | 60 |
| KARDIA 1 | Lignite | STUR | 275 | 50 | 60 |
| KARDIA 3 | Lignite | STUR | 275 | 50 | 60 |
| KARDIA 2 | Lignite | STUR | 280 | 50 | 60 |
| KARDIA 4 | Lignite | STUR | 280 | 50 | 60 |
| MEGALOPOLIS-A NO 1 | Lignite | STUR | 125 | 50 | 60 |
| MEGALOPOLIS-A NO 2 | Lignite | STUR | 125 | 50 | 60 |
| MEGALOPOLIS-A NO 3 | Lignite | STUR | 255 | 50 | 60 |
| MEGALOPOLIS-A NO 4 | Lignite | STUR | 256 | 50 | 60 |
| FLORINA 1 | Lignite | STUR | 289 | 50 | 60 |
| PTOLEMAIS 1 | Lignite | STUR | 70 | 50 | 60 |
| PTOLEMAIS 2 | Lignite | STUR | 116 | 50 | 60 |
| PTOLEMAIS 3 | Lignite | STUR | 116 | 50 | 60 |
| PTOLEMAIS 4 | Lignite | STUR | 274 | 50 | 60 |
| ALIVERI 5 CC 1 | Gas | COMC | 417 | 40 | 30 |
| AGIOS GEORGIOS 8 | Gas | STUR | 151 | 40 | 30 |
| AGIOS GEORGIOS 9 | Gas | STUR | 188 | 40 | 30 |
| KOMOTINI | Gas | COMC | 476 | 40 | 30 |
| LAVRIO-III | Gas | GTUR | 173 | 40 | 30 |
| LAVRIO-IV | Gas | COMC | 550 | 40 | 30 |
| LAVRIO-V CC 1 | Gas | COMC | 378 | 40 | 30 |
| AGIOS NIKOLAOS POWER CC-1 | Gas | COMC | 334 | 40 | 30 |
| THISVI ELPEDISON | Gas | COMC | 410 | 40 | 30 |
| THESSALONIKI POWER | Gas | COMC | 389 | 40 | 30 |
| THIVA HERON-2 CC 1 | Gas | COMC | 435 | 40 | 30 |
| THIVA HERON-1 GT 1 | Gas | GTUR | 48.3 | 40 | 30 |
| THIVA HERON-1 GT 2 | Gas | GTUR | 48.3 | 40 | 30 |
| THIVA HERON-1 GT 3 | Gas | GTUR | 48.3 | 40 | 30 |
| KORINTHOS POWER CC 1 | Gas | COMC | 433 | 40 | 30 |
| CORINTH REFINERY | Gas | GTUR | 45 | 40 | 30 |
| AGIOS NIKOLAOS POWER CC-2 CC 1 | Gas | COMC | 432 | 40 | 30 |
| ALIVERI 3 | Oil | STUR | 144 | 20 | 66 |
| ALIVERI 4 | Oil | STUR | 144 | 20 | 66 |
| LAVRIO HERON | Oil | GTUR | 123 | 20 | 66 |
| LAVRIO-II | Oil | STUR | 287 | 20 | 66 |

(*) COMC: Combined cycle; GTUR: Gas turbine; STUR: Steam turbine

**Table 5.** Techno-economic features of the Greek thermal power plants II.

| Power plant | Cooling (*) | Type (*) | Water consumption factors (*) ($m^3$/MWh) | Water withdrawal factors (*) ($m^3$/MWh) |
|---|---|---|---|---|
| AGIOS DIMITRIOS 1 | NDT | SUBCR | 1.81 | 2.22 |
| AGIOS DIMITRIOS 2 | NDT | SUBCR | 1.81 | 2.22 |
| AGIOS DIMITRIOS 3 | NDT | SUBCR | 1.81 | 2.22 |
| AGIOS DIMITRIOS 4 | NDT | SUBCR | 1.81 | 2.22 |
| AGIOS DIMITRIOS 5 | NDT | SUPERC | 1.87 | 2.40 |
| AMYNTAIO 1 | NDT | SUBCR | 1.81 | 2.22 |
| AMYNTAIO 2 | NDT | SUBCR | 1.81 | 2.22 |
| KARDIA 1 | NDT | SUBCR | 1.81 | 2.22 |
| KARDIA 3 | NDT | SUBCR | 1.81 | 2.22 |
| KARDIA 2 | NDT | SUBCR | 1.81 | 2.22 |
| KARDIA 4 | NDT | SUBCR | 1.81 | 2.22 |
| MEGALOPOLIS-A NO 1 | NDT | SUBCR | 1.81 | 2.22 |
| MEGALOPOLIS-A NO 2 | NDT | SUBCR | 1.81 | 2.22 |
| MEGALOPOLIS-A NO 3 | NDT | SUBCR | 1.81 | 2.22 |
| MEGALOPOLIS-A NO 4 | NDT | SUBCR | 1.81 | 2.22 |
| FLORINA 1 | NDT | SUPERC | 1.87 | 2.40 |
| PTOLEMAIS 1 | NDT | SUBCR | 1.81 | 2.22 |
| PTOLEMAIS 2 | NDT | SUBCR | 1.81 | 2.22 |
| PTOLEMAIS 3 | NDT | SUBCR | 1.81 | 2.22 |
| PTOLEMAIS 4 | NDT | SUBCR | 1.81 | 2.22 |
| ALIVERI 5 CC 1 | OTS | SUBCR | 0.38 | 43.07 |
| AGIOS GEORGIOS 8 | OTS | SUBCR | 0.91 | 132.48 |
| AGIOS GEORGIOS 9 | OTS | SUBCR | 0.91 | 132.48 |
| KOMOTINI | NDT | SUBCR | 0.78 | 0.97 |
| LAVRIO-III | OTS | SUBCR | 0.91 | 132.48 |
| LAVRIO-IV | OTS | SUBCR | 0.38 | 43.07 |
| LAVRIO-V CC 1 | OTS | SUBCR | 0.38 | 43.07 |
| AGIOS NIKOLAOS POWER CC-1 | OTS | SUBCR | 0.38 | 43.07 |
| THISVI ELPEDISON | AIR | SUBCR | - | - |
| THESSALONIKI POWER | MDT | SUBCR | 0.78 | 0.97 |
| THIVA HERON-2 CC 1 | AIR | SUBCR | - | - |
| THIVA HERON-1 GT 1 | AIR | | - | - |
| THIVA HERON-1 GT 2 | AIR | | - | - |
| THIVA HERON-1 GT 3 | AIR | | - | - |
| KORINTHOS POWER CC 1 | AIR | SUBCR | - | - |
| CORINTH REFINERY | AIR | | - | - |
| AGIOS NIKOLAOS POWER CC-2 CC 1 | MDT | SUBCR | 0.78 | 0.97 |
| ALIVERI 3 | OTS | SUBCR | - | - |
| ALIVERI 4 | OTS | SUBCR | - | - |
| LAVRIO HERON | OTS | | - | - |
| LAVRIO-II | OTS | SUBCR | - | - |

(*) **Definitions from Platts' World Electric Power Plant Database**
AIR: Air (dry) main condenser cooling
MDT: Mechanical draft cooling tower, also known as induced draft cooling tower
NDT: Natural draft cooling tower
OTS: Once through cooling using saline water
SUBCR: Subcritical; SUPERC: Supercritical
Water consumption factors are assumed to be the average values collected in [14]
Water withdrawal factors are assumed to be the average values collected in [14]

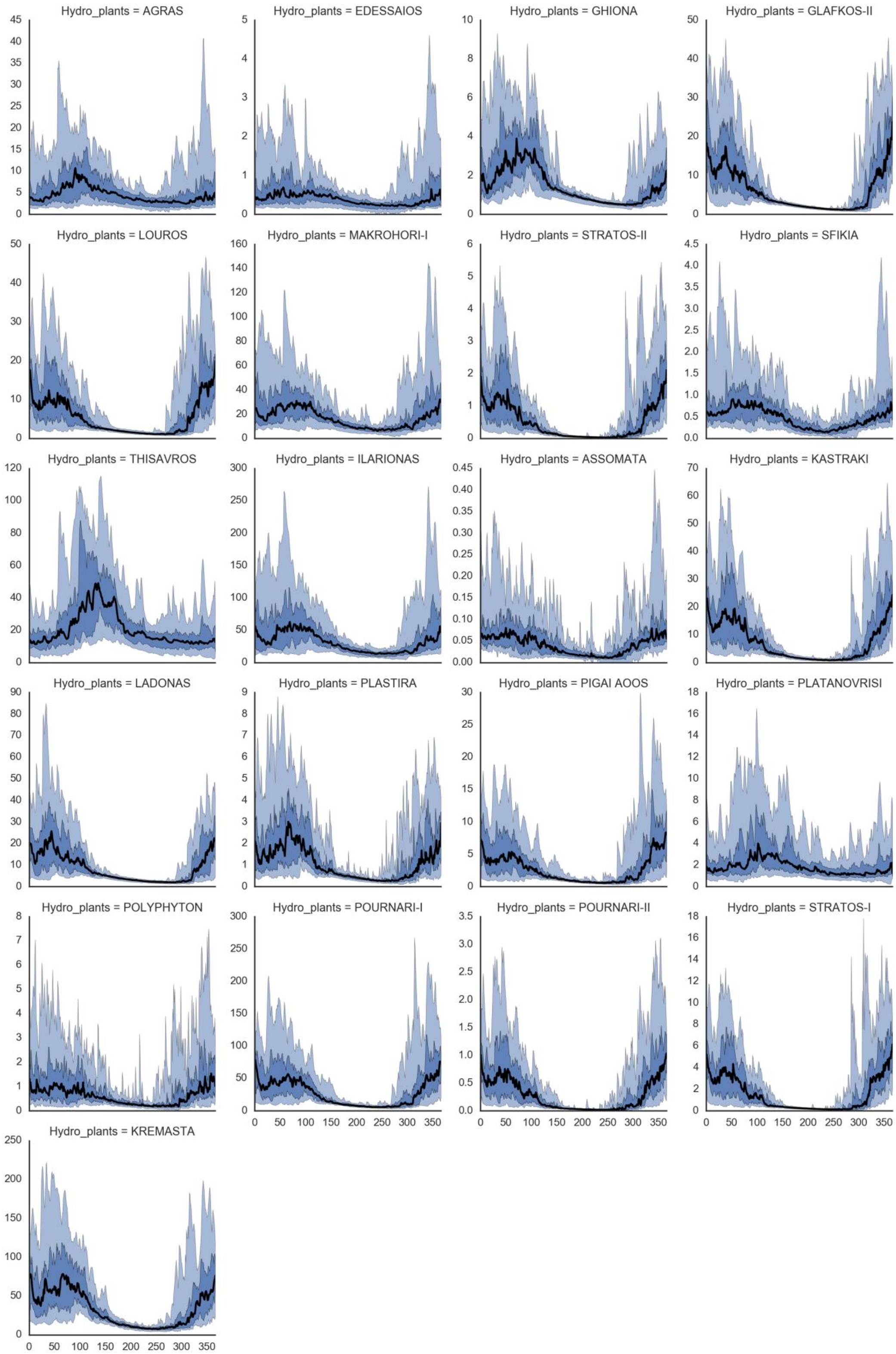
**Table 6.** Techno-economic features of the Greek hydro power plants.

| Power plant | Type | Capacity (MW) | River basin | Storage capacity ($Hm^3$) |
|---|---|---|---|---|
| **Sfikia** | Pumped storage | 315 | Aliakmon | 18 |
| **Thisavros** | Pumped storage | 378 | Nestos | 565 |
| **Agras** | Run-of-river | 50 | Aliakmon | 0 |
| **Edessaios** | Run-of-river | 19 | Aliakmon | 0 |
| **Ghiona** | Run-of-river | 8.5 | Aheloos | 0 |
| **Glafkos II** | Run-of-river | 4.8 | Aheloos | 0 |
| **Louros** | Run-of-river | 10.3 | Arachthos | 0 |
| **Makrohori I** | Run-of-river | 10.8 | Aliakmon | 0 |
| **Stratos II** | Run-of-river | 6 | Aheloos | 0 |
| **Ilarionas** | Reservoir | 77 | Aliakmon | 270 |
| **Assomata** | Reservoir | 108 | Aliakmon | 10 |
| **Kastraki** | Reservoir | 320 | Aheloos | 53 |
| **Ladonas** | Reservoir | 70 | Ladon | 46 |
| **Plastira** | Reservoir | 130 | Tavropos | 300 |
| **Pigai Aoos** | Reservoir | 230 | Aoos | 144 |
| **Platanovrisi** | Reservoir | 116 | Nestos | 57 |
| **Polyphyton** | Reservoir | 375 | Aliakmon | 1220 |
| **Pournari I** | Reservoir | 300 | Arachthos | 303 |
| **Pournari II** | Reservoir | 33.6 | Arachthos | 4 |
| **Stratos I** | Reservoir | 150 | Aheloos | 11 |
| **Kremasta** | Reservoir | 437 | Aheloos | 3300 |

## Annex 2: Inflows time series

Different percentiles for the historical time series of net inflows are presented in Figure 31.

**Figure 31.** Historical time series of net inflows ($m^3/s$) for a year per reservoir. The $5^{th}$, $25^{th}$, $50^{th}$ (black line), $75^{th}$, and $95^{th}$ percentiles are presented



## Annex 3: Water stress index

For the sake of completeness, figures 32-37 provide the historical water stress index for the thermal power plants "Amyntaio", "Kardia", "Komotini", "Florina", "Ptolemais", and "Thessaloniki power".

**Figure 32.** Historical water stress index for the "Amyntaio" power plant

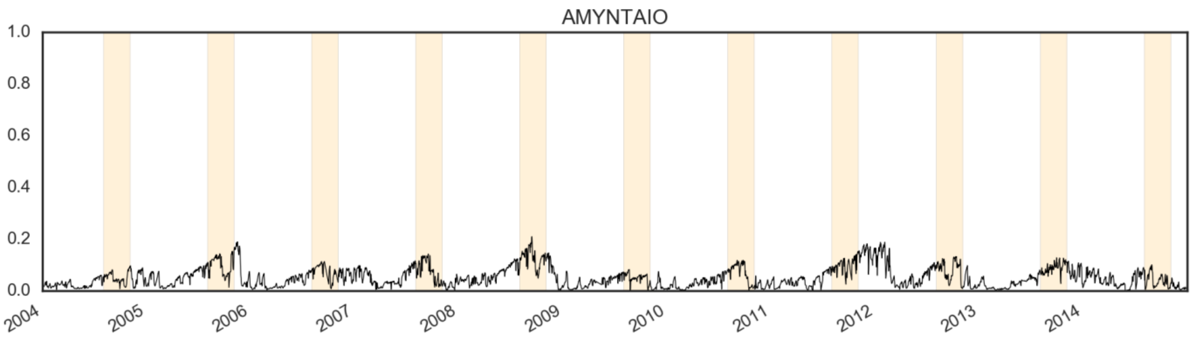



**Figure 33.** Historical water stress index for the "Kardia" power plant

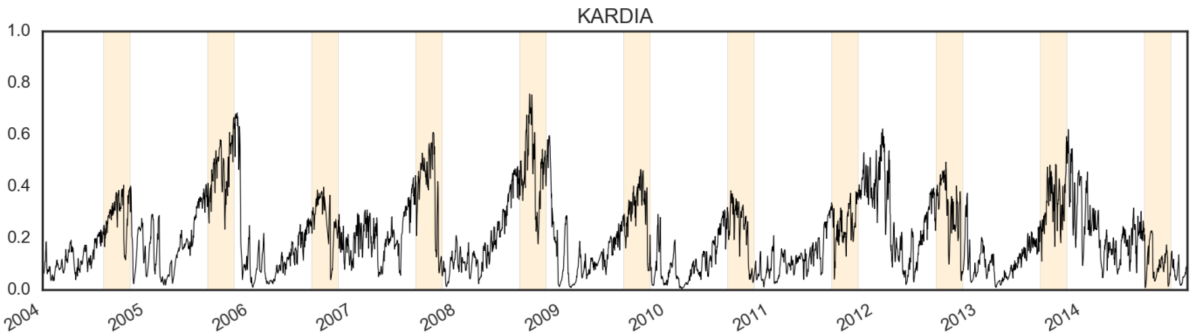



**Figure 34.** Historical water stress index for the "Komotini" power plant

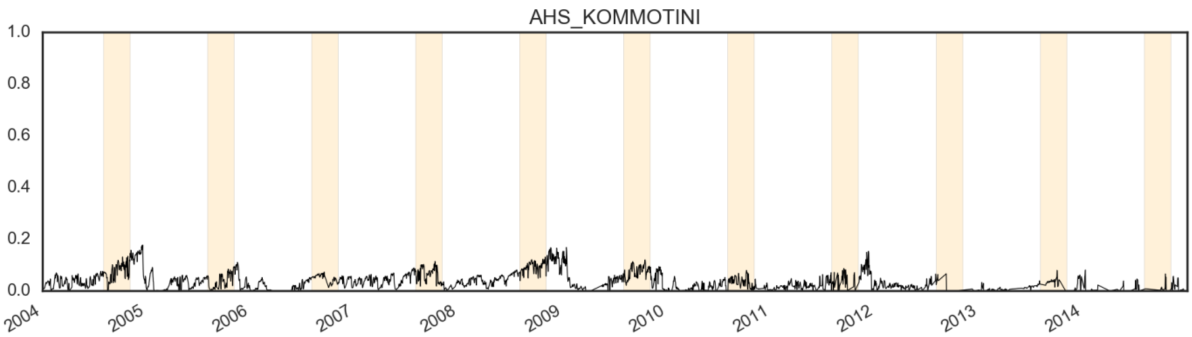


**Figure 35.** Historical water stress index for the "Florina" power plant

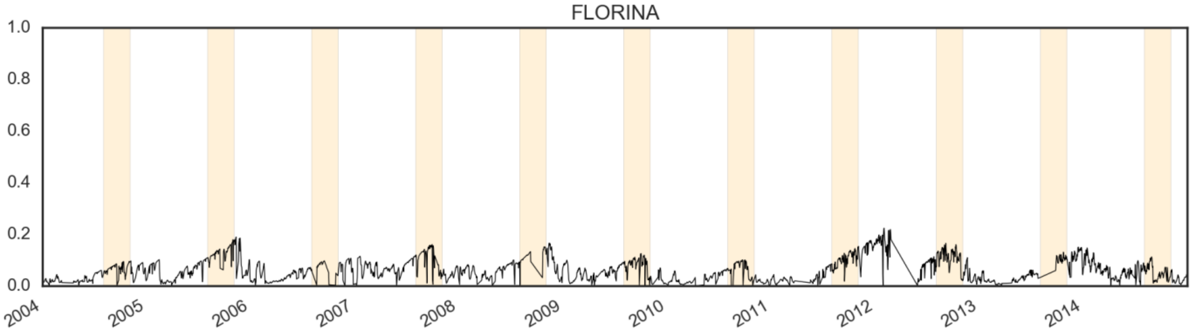



**Figure 36.** Historical water stress index for the "Ptolemais" power plant

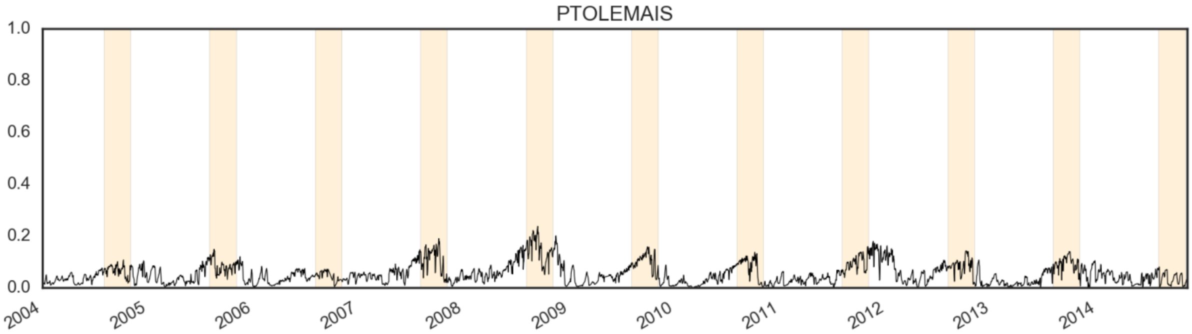
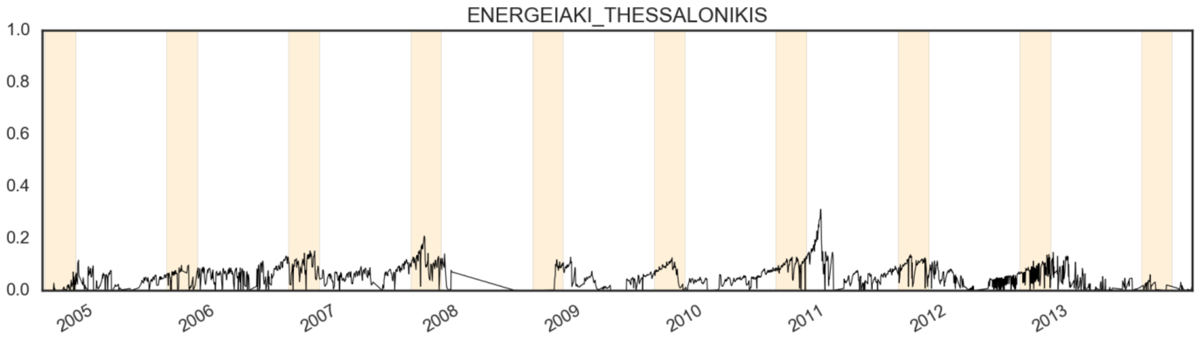



**Figure 37.** Historical water stress index for the "Thessaloniki power" power plant



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