Analysis of the water-power nexus of the Balkan Peninsula power system

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Abstract

Power generation sector worldwide accounts for high water withdrawal and consumption due to the hydropower generation and cooling of thermal power plants. Hence, the operation of the power generation sector is constrained by the availability of the water resources, as well as the addition of constrains on water resources used for other purposes, such as irrigation, flood control, water supply, agriculture, etc. The optimal utilization of water resources between the water and energy sector is defined under the term water-energy (or water-power) nexus. This study describes the implementation of hydrological LISFLOOD, Medium-Term Hydrothermal Coordination (MTHC) and Unit Commitment and Dispatch (DispaSET UCD) models for detailed analysis of impacts on the SEE regional power system for three different hydrological years. Results were validated based on the available ENTSO-E data for the average hydrological (2015) year. Results show increase in hydropower generation from 53.06 TWh for dry year, to 65.24 and 85.13 TWh for average and wet year, respectively, while the average electricity cost falls from 17.79 EUR/MWh for dry year, to 16.36 and 14.05 EUR/MWh for average and wet year, respectively. This analysis successfully replicates the methodology under the WATERFLEX project, with the novelty in run-of-river hydropower generation calculations in MTHC model.

Keywords: energy modelling, water-energy nexus, Dispa-SET, LISFLOOD

1. Introduction

Power generation accounts for high water withdrawal and consumption as a result of hydropower generation and thermal power plant cooling. Besides the water use for power sector, water resources are used for a variety of purposes not related to the power sector, such as irrigation, flood control, water supply, agriculture etc. [1]. Several examples of water resource shortages or high river temperatures have been experienced in the last decade. Due to joint effects of bad hydrological conditions and heat waves, several French nuclear power plants in 2013 had to curtail power generation, which generated additional cost of EUR 300 million. In 2006., France, Germany and Spain had to reduce their nuclear power generation due to the high river water temperatures. Poland experienced reduced coal power generation and restricted industrial demand in 2015-2016 due to the same reasons [2]. This forced flexible generation of the inflexible thermal power plants results in demand restrictions, monetary losses and increased wear of generation units. Furthermore, recent examples of unplanned outages in France, Germany and Switzerland have been experienced in 2018 [3]. Mentioned impacts with the forecasts that climate change will cause a number of similar events to rise, raise the questions on how to implement better water management.

The term water-energy nexus is used to refer the interactions between the water and energy sectors for the best utilization of water resources. The hydropower is recognized technology that provides benefits for the total power system operation, such as black start capability, spinning reserve, frequency response, flexibility and reserve with quick start and shutdown capabilities. Mentioned hydropower characteristics identify hydropower as a main cost-competitive resource for integration of variable renewable sources into the European power system [1]. Importance of water-energy nexus is recognized as new challenge for better control of water resources, but present power system models overlook water-related constraints to power system and water resources management. Hydrological related constraints determine hydropower production, which in turn determine the operation of thermal power plants related to its water sources for proper cooling. Thus, the better understanding of the water-energy nexus is needed to enable flexible power generation for the future European power system [2]. With projections of the future extreme droughts in summer and floods in the winter/autumn, adaptation of the hydropower units to a climate change relies on optimal management of water reservoirs [4].

Water-energy nexus has been a popular research topic in a last decade. International Energy Agency started discussion on the energy and water dependence in 2012 in a chapter “Water for Energy: Is energy becoming a thirstier resource?” from the World Energy Outlook 2012 [5]. More thoroughly discussion on the same topic can be found in 2016 World Energy Outlook [6]. US Department of Energy published extensive data and analysis report on water-energy nexus with intention of connecting and encouraging relevant stakeholders in a dialog and joint actions to address the water-energy challenges [7]. Joint cooperation between US Department of Energy, European Commission’s Joint Research Centre (JRC) and Directorate-General for Research and Innovation led to organization of a workshop dedicated to understanding the water-energy nexus, with higher emphasis on integrated water and power system modelling [8]. More recent reports published by the JRC introduce integrated analysis of the independencies between energy and agricultural water demand, drinking and urban water provision, and ecosystem flow requirements under the Water Energy Food and Ecosystem (WEFE) Nexus [9], [10]. The report [9] provides a first summary of the WEFE Nexus findings regarding the water and energy usage in Europe, with more emphasis on water availability. Furthermore, report concludes the importance of development of integrated model, and presents coupling water and energy model-based assessments for better understanding of the water-energy nexus. Moreover, policy recommendations are divided into strategic and operational ones, where strategic measures represent long-term actions, while operational measures are based on the existing technological solutions. The Position Paper [10] outlines the importance of the WEFE Nexus as a methodology aiming to an integrated management across water, energy and food security, while ensuring the sustainable usage of ecosystem resources. Moreover, it presents the thoughts and lessons learnt from the experts that attended the 2018 Nexus workshop, adding the recommendations on how to implement the WEFE Nexus approach. The position paper adds on importance of the scientific-technical dimensions as supporting element that provides scientific evidence for evidence-based policy making.

In [2] authors studied the water-energy nexus for a Greek power system. They analysed the implications of water on the energy system and vice versa for three different historical scenarios. Moreover, the addition of water stress index (WSI) is used to determine the locations and time frames with high possibility of water scarcity under the dry hydrological conditions. The same approach was used by authors in [11], with addition of vulnerability analysis of cooling-related constraints on allowable water withdrawal for two different power producing units. The analysis included water withdrawal constraints on coal-fired power plants with high marginal cost and moderate installed capacity, and nuclear power plant representing technology with low marginal cost and high installed capacity. The study [12] includes the water-energy nexus analysis done on the Spanish energy system. Authors reviewed the published work on Spanish water system, with emphasis on separate study of energy-for-water and water-for-energy. The energy-for-water study includes dividing water use stages and calculation of energy cost for water use, with special consideration on irrigation. On the other hand, water-for-energy study includes evaluation of water needs for power plant cooling. D Zafirakis et. al. in [13] studied the water needs in the Greek electricity sector concluding that promotion of renewable energy sources will ensure conservation of water resources in vulnerable regions. Authors collected the data on operation of thermal power units and renewable technologies to determine the minimum water needs and compared it to existing technologies. Furthermore, authors indicate that water withdrawal coefficient for lignite-fired power plants is as high as expected, but the calculated water consumption coefficient is lower than the ones in available data bases. They finished with the conclusion that high RES technologies penetration in water scarce region, such as West Peloponnesus, Crete and West Macedonia, might resolve local water scarcity problems. The water-energy nexus for Greece region was also studied in [14]. Authors provided calculations on water consumption of several different processes. Calculation included processes of electricity generation in conventional thermal power units, such as lignite, diesel, oil and gas-fired units, production of biodiesel, and extraction and refining processes in the primary energy producing sector. To connect the water consumption with energy, they provided the calculation of electricity consumption for purposes of water supply and water treatment. Authors conclude that the most water-intensive sector includes power generation from lignite and oil-fired thermal power plants averaging at water consumption of 1.81 m^3/MWh, followed by CCGT units with water consumption of 1.19 m^3/MWh. The biofuel production accounts for nearly 0.5 m^3/MWh, while the primary fuel production requires the least amount of freshwater. Moreover, the authors conclude that water supply is much more energy-intensive, when compared to the water treatment processes. Authors in [15] and [16] study the Spanish energy sector adaptation to available water resources, as well as integration of water and energy models. The study in [15] is review of available models and recommendations for the future work, including the literature on water-energy nexus. Furthermore, need for water and energy sector integration, as well as barriers in integrated water and energy modelling, with list of recommendations is thoroughly discussed in the study. In [16] authors took the approach of comparing two different scenarios. Stressed scenario represents integrated water-energy model which takes water constraints into account, while Unconstrained scenario is traditional non-integrated energy model that neglects the importance of water constraints on energy sector. They came with the results that neglecting the water constraints results with unpredicted costs under the climate change scenario. Moreover, authors estimate that the cost of neglecting the water constraints in the future water-restricted scenarios may range from 0.2% and 8% of the total system cost, which is more than double of adaptation costs. Water stress vulnerability of electricity generation units in the EU region was studied in [17]. Study included 1326 thermal power units and 818 water basins. Authors used year 2014 as reference year, and projection scenarios for 2020 and 2030. Furthermore, study shows energy-water-climate model that integrates power plant, water quantity and water temperature databases. Model also includes the adaptation strategies, such as usage of air cooling for planned and constructed units, additional use of seawater for coastal units cooling, early retirement of older units, and replacement of planned power capacities with renewable energy sources. Results show that regions that experience reduction in power generation due to the waters stress increase from reference 47 to 57 basins between 2014 and 2030, while including water demand for non-energy related processes. Moreover, authors conclude that highly vulnerable regions are Mediterranean regions, Germany, Bulgaria, Poland and France. Pereira-Cardenal, S.J. et. al. in studies [18], [19] and [20] focused on interactions between water and energy system to identify methods that could be used to assess spatial-temporal interactions in water-energy nexus. Authors used the approach of including water and energy sector in joint optimisation problem with objective function composed of power production costs, while maximizing the benefits of water allocations. Link between two systems is described using constraints in optimization problem and solved using stochastic dynamic programming. Authors used Iberian

Peninsula as case study for method implementation. Authors conclude that climate change may reduce hydropower generation by 24%, increasing thermal power generation and CO_2 emissions. Moreover, authors recommend topics for future research, such as more realistic representation of power market using the hourly values, and further spatial disaggregation of the hydrological system. Authors in [21] made a comprehensive review of existing optimisation techniques and approaches in planning and design of water supply side in water-energy nexus with objective to identify research gaps. Authors conclude that research on water-energy nexus lacks the holistic approach, and that the problem is mostly addressed from either water or energy side. Authors also add that most of the studies ignore the uncertainties of used parameters in the optimisation models. The water-energy nexus for the US region was studied in [22] and [23]. In [22] the economic implications were studied for shifting from coal to natural gas, and replacement of open-loop with the closed-loop cooling technologies. Results show that on average shift from coal to natural gas saves 32% of water consumption and 37% of water withdrawal. Shift from open-loop to closed-looped system shows the 96% decrease in water withdrawal and 58% increase in water consumption. In [23] the analysis of 2011 droughts was studied to examine the power plant's vulnerability regarding moderate year 2010. The water consumption in energy-related sectors and the energy consumption in water-related activities were studied, with a discussion on energy and environmental implications for the MEAN region in a study [24]. Authors in [25] developed a model to determine economic impacts, the water consumption and withdrawal, and detailed operation of the power system under different current and future scenarios. Based on a modelling framework developed by the JRC, authors study the water-energy nexus for the West African Power Pool. Results show that future power system operation of the Western African Power Pool regions significantly depends on the water availability, which translates in high volatility of the system cost. Hence, the future policy scenarios should use the technologies that will be most suitable to achieve low volatility, low cost and low emissions. Implementation of Dispa-SET UCD model to the six Western Balkan countries is shown in [26]. Authors were using Dispa-SET UCD to prove the hypothesis stating that it is possible to phase out large amount of lignite-powered power units and replace it with renewable energy sources without compromising the flexibility and stability of the power system. The referenced scenario for 2010 including power systems of Albania, Bosnia and Herzegovina, Kosovo, Macedonia, Montenegro and Serbia was developed and validated. Two additional scenarios that include implementation of national energy strategies for 2020 and 2030 were analysed. Results showed that high RES integration coupled with expansion of cross-border interconnections increases the region's energy independence and security of supply. Authors in [27] used Dispa-SET UCD model on Western Balkan countries with addition of Croatian and Slovenian power systems. Model was developed for three different years, 2015, 2030 and 2050 used for testing various modelling formulations. The goal of the research was to test usefulness of different types of clustering techniques to lower the computational time. In three different clustering approaches results showed that computation time was 1.4, 2.1 and 19 times lower that the no clustering approach.

Water resources have always been important for the Balkan Peninsula economy with its use for irrigation, drinking water supply, tourism, industry, livestock production and hydropower generation. The hydropower generation accounts for 49% of all electricity generated in the Western Balkan region [4]. Projections are that Balkan Peninsula is getting warmer and that trend will continue with the expected increase in global temperatures due to climate change. Even though precipitation rate changes with terrain, elevation and proximity to the sea, the region is experiencing lower annual precipitation with projections for a further decrease. Worst case scenario, a 4°C temperature rise, by the projections in [28] states that Balkan Peninsula Region could encounter reduced water availability with projections of precipitation declining between 20-50%. As most countries in the Balkan region depend on hydropower generation, reduction in water availability would strongly affect the region power system. Moreover, due to the increased possibility of extremely low river flows in summer days, the mean number of days during which electricity production will be reduced by more than 90% is projected to increase.

This study illustrates the implementation of three models for detailed analysis of impacts on the regional power system due to different hydrological conditions. Case study includes Balkan Peninsula region covering analysis of countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Hungary, Kosovo, Montenegro, North Macedonia, Romania, Serbia and Slovenia. For the water-energy nexus analysis, method includes combining hydrological LISFLOOD model, Medium-Term Hydrothermal Coordination model (MTHC) and Dispa-SET Unit Commitment and Dispatch model (Dispa-SET UCD). Hydrological LISFLOOD model is used as source of water inflow data needed as input for two energy models. The first MTHC energy model, determines reservoir accumulation levels for hydropower units during one-year time period, as well as the hydropower generation from run-of-river units. Results from the MTHC model are used as input data for Dispa-SET UCD model that results in power generation, economical, and commitment and power dispatch values for each power unit included in the model.

The remainder of the paper is as follows: Section 2 describes the models used to analyse the water-energy nexus. Section 3 covers input data regarding the modelled region, as well as the scenario definition. Section **Error! Reference source not found.** provides results and discussion, while the Section 5 presents conclusions of the provided study.

2. Methodology

Two energy models, MTHC and Dispa-SET UCD models are both linked to the hydrological LISFLOOD model. LISFLOOD model is used as input data in form of water inflows used for calculation of reservoir levels and run-of-river hydropower generation. MTHC model runs at daily time step to provide results on management of the water resources. Reservoir level and run-of-river hydropower generation as results from MTHC model, is used as input data from Unit Commitment and Dispatch model. Dispa-SET UCD model runs at the hourly time step and results in power dispatch and schedule, water-related and economic values.

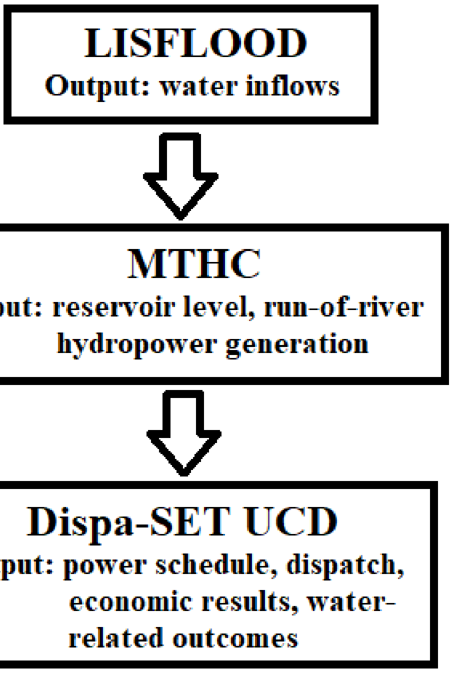

Figure 1. Modelling steps

2.1. LISFLOOD Hydrological model

The LISFLOOD model will be only briefly described as its available output data are used as input values for two energy models. The LISFLOOD model has been developed by the floods group of the Natural Hazards Project of the Joint Research Centre. It is the hydrological rainfall-runoff model that simulates the hydrological processes in a catchment including flood forecasting, effect of the land-use change, assessing the effects of river regulation measures, and effects of climate change [29]. The model is designed to be used across a wide range of spatial and temporal scales. Since it is grid-based, the model can be used on a grid cells ranging from as little as 100 meters for the medium-sized catchments, and up to 10 km for global models. The time steps can be daily based for the simulation of the long-term water balance, while the hourly time steps are used for the simulation of the individual flood events. Also, the output of the "water balance" simulation can be used as input data for the "flood" simulations. Even though the primary output is channel discharge, all the internal rate and states variable can be written as the output with the complete user control.

The model is made up of the two-layer soil water balance sub-models, sub-models for the simulation of groundwater and subsurface flow, sub-model for the routing of channel flow, and sub-model for the routing of surface runoff to the nearest river channel. Simulated processes include infiltration, snowmelt, leaf drainage, surface runoff, evaporation, interception of rainfall, water uptake by vegetation, exchange of soil moisture between soil layers, drainage to the groundwater, bypass of the soil layer and flow through the river channel. More on the formulation of the mentioned processes can be seen in [29].

2.2. Medium-Term Hydrothermal Coordination model

The MTHC model is used to determine operation planning of hydropower reservoirs and thermal power plants based on minimization of system cost function composed of the system generation costs over a given planning horizon. The time horizon ranges from one year to several years with daily, weekly or monthly times steps. The degree of detail of hydropower units is greater than in the short-term operation at the expense of clustering the same fuel-powered thermal power plants. That suggests that thermal power units are aggregated by fuel and country, due to the main scope of the MTHC model being results on hydropower generation and reservoir levels. Inclusion of each thermal power unit itself would substantially increase the run time of the model. The MTHC problem can be characterized as large-scale, nonlinear and nonconvex optimization.

The MTHC problem can be solved from two perspectives. The extensive form also knows as deterministic equivalent assumes fixed water inflows, and regarding the formulation of the hydro and thermal related technical features, can be formulated as linear programming, mixed-integer linear programming, and non-linear programming. On the other hand, stochastic form includes uncertainty of hydrological scenarios for each planning stage that consist of the amount of water resources available for the power generation at each stage of the time horizon. Stochastic problem can be solved vertically by stage/time, or horizontal by scenarios, and are mostly used in situations of inherent uncertainty of different variables that could affect real-time operational decisions. [30]. The deterministic approach is used for scenario-based analysis and it is used in this paper to define constraint linear programming problem in GAMS.

The model sets are shown in **Table 1***, variables in* **Table 2** *and model parameters in*

Table ***3***.

Table 1. MTHC model sets

Sets	
p	Time periods
ut	Thermal power plants
ur	Renewable power units: SUN, WIN, HROR
uh	Hydropower plants with storage
up	Pumped storage hydropower plant
l	Lines (Transmission lines between neighbouring countries)

n	Nodes (Countries)
t	Technology

Table 2. MTHC model variables

Name	**Unit**	**Description**
G (*p*,*u*)	GWh	Energy generated in period *p* by power plant *u*
PUMP (*p*,*u*)	GWh	Pumping water at period *p* to storage of plant *u*
RES (*p*,*u*)	Mm^3	Water stored at period *p* in plant *u*
DIS (*p*,*u*)	m^3/s	Water discharge at period *p* by plant *u*
CH (*p*,*u*)	m^3/s	Water charge at period *p* to pumped hydro storage *u*
SPILL (*p*,*u*)	m^3/s	Spillage at period *p* by plant *u*
UPSTREAM (*p*,*u*)	m^3/s	Inflow from upstream hydropower plants at time *p* for plant *u*
FLOW (*p*,*l*)	GWh	Energy transmission at period *p* and line *l*
CURT (*p*,*n*)	GWh	Curtailed RES at time *p* in node *n*
LOSTLOAD (*p*,*n*)	GWh	Unsatisfied demand at time *p* in node *n*

Table 3. MTHC model variables

Name	**Unit**	**Description**
dt	h	Period duration
Gravity	m/s^2	Gravity constant
Density	kg/m^3	Water density
F_1	GWh/((m3/s)·m)	Conversion factor from m3/s to GWh
F_2	Mm3/(m3·s)	Conversion factor from m3/s to Mm^3
Technology (*u*,*t*)	/	Power generation technology
Demand (*p*,*n*)	GWh	Electricity demand for the node *n* at period *p*
Duration (*n*,*t*)	day	Minimum number of days a given technology must be producing to match statistics
Location (*u*,*n*)	/	Unit location
Pmin (*u*)	GW	Minimum stable generation of unit
Pmax (*u*)	GW	Installed capacity
VarCost (*u*)	k€/GWh	Variable cost of electricity generation
Stmin (*u*)	Mm^3	Minimum storage level
Stmax (*u*)	Mm^3	Maximum storage level
Stinit (*u*)	Mm^3	Initial storage level
eta_pump (*u*)	%	Pumping efficiency
eta_turb (*u*)	%	Discharging efficiency
Delay (*u*, *uu*)	day	Water transport delay between two unit *u*
NominalHead (*u*)	m	Nominal head of hydropower plant
Resources (*p*,*u*)	m^3/s	Natural water inflows
Evaporation (*p*,*u*)	m^3/s	Evaporation loses from reservoirs
Profiles (*p*,*u*)	/	Capacity factor for solar and wind power
Topology (*u*,*uu*)	/	Hydropower network (Cascades)
Spillage_max (*p*,*u*)	m^3/s	Maximum spillage allowed
Incidence_matrix (*n*,*l*)	/	Line-node incidence matrix for power flow
LineCapacity (*l*)	GW	Transmission line capacity
DemandW (*p*,*u*)	m^3/s	Water withdrawal from plant *u* at period *p*
Eco_flow (*p*,*u*)	m^3/s	Environmental flow
Availability (*p*,*u*)	%	Unit availability

The objective can be seen in equation (1). The objective function determines the total electricity generation cost during the simulation period. The objective function includes variable costs of power generation for all units, pumping costs in pumped-storage hydropower units, spillage of excess of water, energy transmission, energy curtailment and load shedding.

$$\begin{aligned} SystemCost = {} & \textstyle\sum_{p,u} VarCost(u) \cdot G(p,u) + \sum_{p,u} PumpingCost \cdot PUMP(p,u) + \\ & \textstyle\sum_{p,u} SpillageCost \cdot SPILL(p,u) + \sum_{p,u} TransmissionCost \cdot FLOW(p,l) + \\ & \textstyle\sum_{p,u} CurtailmentCost \cdot CURT(p,n) + \\ & \textstyle\sum_{p,u} LostLoadCost \ \cdot LOSTLOAD(p,n) \end{aligned} \tag{1}$$

The objective function is constrained by a set of equations:

The market clearing equation (2) state that for each node *n* at period *p* the supply (generation and imports of electricity) must meet the demand:

$$\begin{aligned} \textstyle\sum_{u\in U(n)} G(p,u) + \sum_{l\in L(n)} FLOW(p,l) = {} & Demand(p,n) + \textstyle\sum_{u\in PUMP(n)} PUMP(p,u) + \\ & CURT(p,n) - LOSTLOAD(p,n) \end{aligned} \tag{2}$$

In equation (3) minimum and maximum generation bound are set. It determines minimum and maximum power generation capabilities of each unit in every time step:

$$Pmin(u) \cdot dt < G(p,u) < Pmax \cdot dt \tag{3}$$

Equation (4) represents energy generation by hydropower units.

$$G(p,u) = eta\_turb(u) \cdot DIS(p,u) \cdot NominalHead \cdot F_1 \tag{4}$$

Equation (5) shows F_1 factor used to calculate hydropower generation in GWh.

$$F_1 = 24(h) \cdot 60(min/h) \cdot 60(s/min) \cdot Gravity \cdot Density \cdot \frac{1}{3600}\left(\frac{Wh}{J}\right)\frac{1}{10^9}\left(\frac{GWh}{Wh}\right) \tag{5}$$

Renewable energy generation is calculated using equation (6).

$$G(p,u) = Pmax(u) \cdot Profiles(p,u) \cdot dt \tag{6}$$

Equation (7) sets the line capacities between the modelled countries.

$$FLOW(p,l) \leq LineCapacity(l) \cdot dt \tag{7}$$

Equation (8) is water balance equation for the available water resources for each node *n* at period *p*. Factor F_2 is used to convert water resources from m^3/s into Mm^3.

$$\begin{aligned} RES(p,u) - RES(p-1,u) = F_2 \cdot (& Resources(p,u) - Evaporation(p,u) + \\ & UPSTREAM(p,u) + CH(p,u) - DIS(p,u) - \\ & SPILL(p,u) - DemandW(p,u)) \end{aligned} \tag{8}$$

Minimum and maximum available reservoir storage is set by the equation (9)

$$Stmax(p,u) \geq RES(p,u) \geq Stmin(p,u) \tag{9}$$

Pumped hydropower plant pumping mode is described by the equation (10), while equation (11) sets the maximum pumping power capacity for the each unit.

$$PUMP(p,u) = CH(p,u) \cdot NominalHead(u) \cdot F_1 \cdot \frac{1}{eta\_pump} \tag{10}$$

$$PUMP(p,u) \leq Pmax(u) \cdot dt \tag{11}$$

2.3. Dispa-SET Unit Commitment and Dispatch model

Dispa-SET UCD model aims to represent operation of the large-scale power system and it consists of two parts. First part is scheduling the start-up, shut down and operation of available generation units. The problem requires the use of binary variables to be able to represent the start-up and shut down decisions, while also considering constraints connected to the commitment status of the generation units in all time periods. Second part of the problem is allocation of the total power demand to be achieved among the available generation units to achieve minimization of total power system cost. This part of the problem is the economic dispatch problem, which determines the output of all generation units. The problem can be formed as a mixed integer linear problem (MILP) or simplified linear program (LP) depending on the picked level of details for the input data. The implementations of both problems (MILP and LP) exists in both GAMS and PYOMO and can be in more details found in [31].

Continues variables include dispatched power, shed load and curtailed power generation in every time step, while commitment status of each unit represents binary variables. The model features include: minimum and maximum power outputs for the all units, up and down reserves, minimum up and down times, load shedding, ramping limits, curtailment, pumped-hydro storage, non-dispatchable units, outages of all units, constraints on the targets for the renewables and/or CO2 emissions, schedules for the reservoir storage level, constraints of CHP units and thermal storage, network-related constraints, different clustering methods and costs of start-up, ramping and no load. More on model sets, variables and parameters can be found in [31].

Dispa-SET UCD objective function is composed of all relevant power system costs, such as start-up and shut down costs, fixed, variable, ramping, transmission-related, load shedding and lost load costs. Objective function can me seen in equation (12).

$$\begin{aligned} SystemCost = \sum_{u,n,i} \big[& CostStartUp_{u,i} + CostShutDown_{u,i} + CostFired_{u} \cdot Committed_{u,i} \\ & + CostVariable_{u,i} \cdot Power_{u,i} + CostRampUp_{u,i} + CostRampDown_{u,i} \\ & + PriceTransmission_{i,l} \cdot Flow_{i,l} + CostLoadShedding_{i,n} \cdot ShedLoad_{i,n} \\ & + CostHeatSlack_{chp(u),i} \cdot HeatSlack_{chp(u),i} \\ & + CostVariable_{chp(u),i} \cdot CHPPowerLossFactor_{chp(u)} \cdot Heat_{chp(u),i} \\ & + VOLL_{Power} \cdot \left(LostLoadMaxPower_{i,n} + LostLoadMinPower_{i,n}\right) \\ & + VOLL_{Reserve} \cdot \left(LostLoadReserve2U_{i,n} + LostLoadReserve2d_{i,n}\right) \\ & + VOLL_{Ramp} \cdot \left(LostLoadRampUp_{u,i} + LostLoadRampDown_{u,i}\right) \big] \end{aligned} \tag{12}$$

The main constraint equation is the supply-demand balance in the day-ahead market. In the equation (13), the sum of all power produced by the units in node *n*, the power imported from neighbouring nodes and the curtailed power must be equal to the sum of the load and power consumed for energy storage, minus the load interrupted and the load shed.

$$\begin{aligned}\sum_{p,u} Power_{u,i} \cdot Location_{u,n} + \sum_{p,u} Flow_{l,i} \cdot LineNode_{l,n} \\ = Demand_{DA,n,h} + \sum_{p,u} StorageInput_{s,h} \cdot Location_{s,n} - ShedLoad_{n,i} \\ - LL_{MaxPower,n,i} + LL_{MinPower,n,i}\end{aligned} \tag{13}$$

Other constraints related to the reserves, ramping, storage, power output, minimum up and down times, heat production, heat storage, network, emissions, curtailment and load shedding can be seen in [31].

3. Case Study and scenario definition

Balkan Peninsula Region is dependent on energy import, especially the oil and natural gas imports, with the high dependence and use of coal, primarily lignite, in power generation. Besides the high carbon density due to the heavy dependence on coal, the excessive use of wood for fuel is a significant environmental concern, as it is the cause of air pollution, deforestation and land degradation [4].

In **Figure 2** percentage share of installed capacities in Balkan Region can be seen. Countries Albania, Croatia and Montenegro have more than 50% of installed capacities in form of thermal power units. The highest share of thermal power units is in Hungary and Kosovo, with percentages of 90% and 89%, respectively. In Hungary, nuclear power plant account for 24%, whilst the rest of percentage is related to the fossil-fired thermal power units, mostly gas-fired units. The 89% of thermal power units in Kosovo are lignite-fired thermal power units. Bulgaria, Greece and Romania have the highest share of installed thermal unit capacities, with 7963, 8804 and 12 247 MW, respectively. Excluding nuclear power units, the highest percentages of fossil-fired units are in Hungary, Kosovo and Serbia, with percentages of 67, 89 and 61%, respectively. Countries with highest share of hydropower generation are Albania, Bosnia and Herzegovina and Croatia with shares of 95, 45 and 46%, respectively. Countries with highest installed hydropower capacities are Bulgaria, Greece and Romania with installed capacities of 3204, 3172 and 6490MW, respectively. Excluding hydropower, countries with high renewable energy sources are Greece, Romania, Bulgaria and Croatia, with shares of 14, 14, 29 and 18%, respectively. Countries with highest installed renewable energy source capacities are Bulgaria, Greece and Romania, with capacities of 4314, 1744 and 4796 MW, respectively.

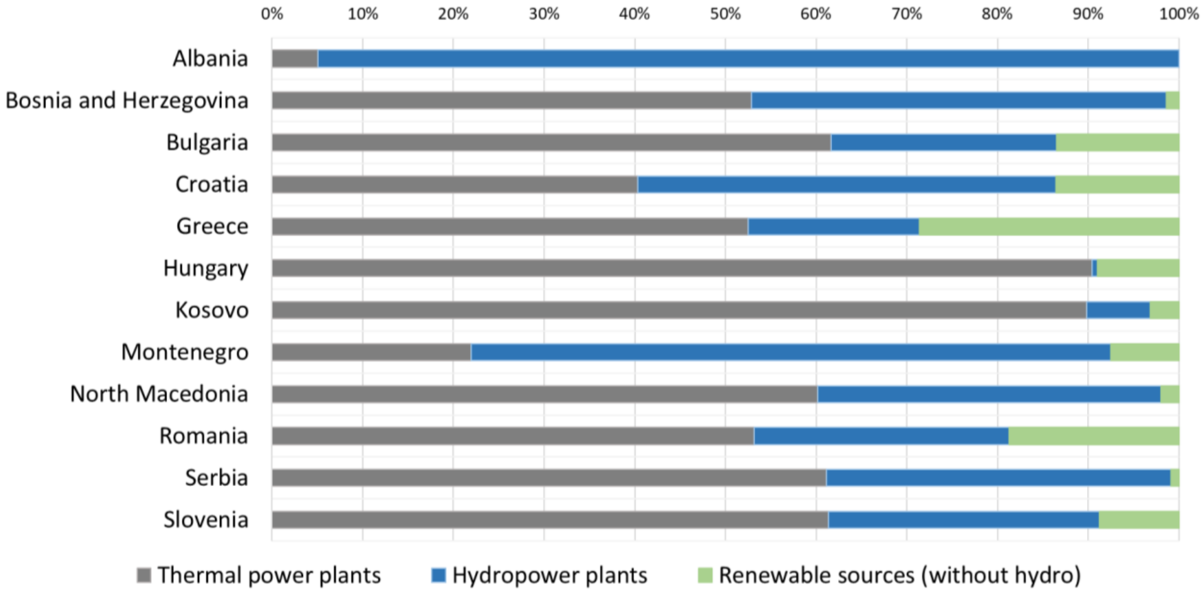

Figure 2. Percentage share of installed capacities in Balkan Region

The study includes scenario-based analysis regarding three different hydrological years. Net water inflows have been provided by the JRC from the rainfall-runoff hydrological LISFLOOD model briefly described in Section 2.1. The assumption is that the provided water inflows are the total runoff at studied catchment level. **Figure 3** shows total water inflows for the included hydropower plants locations for a period between 1990 and 2016. The yellow highlighted line represents the runoff for the dry (2007), green highlighted for the average (2015), and red highlighted for the wet (2010) year.

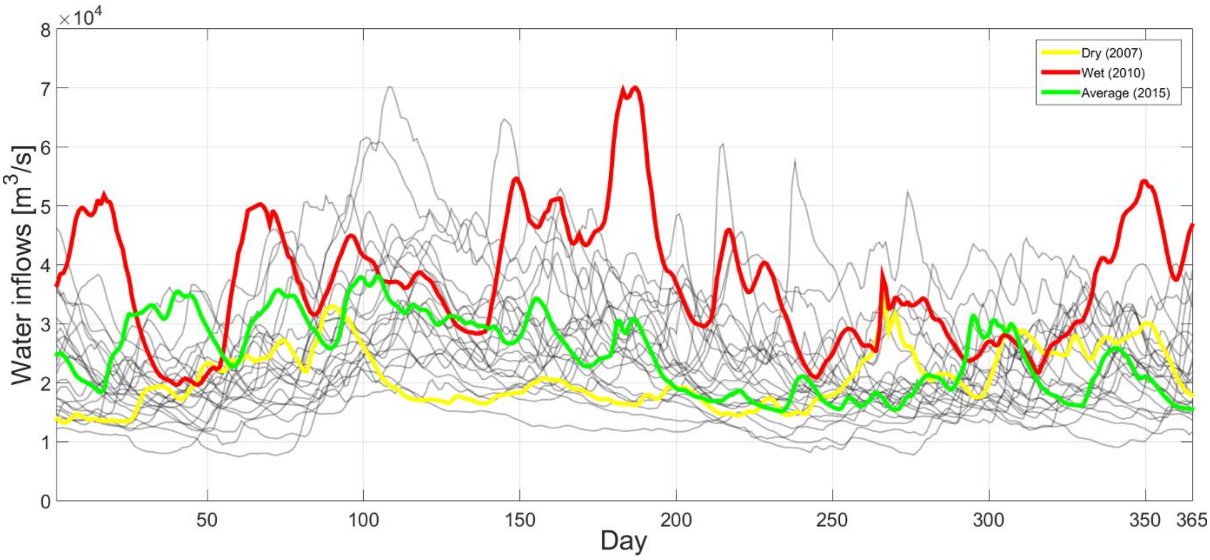

Figure 3. Total water inflows for the studied region. Years between 1990 and 2016

4. Model results

4.1. Medium-Term Hydrothermal Coordination model results

Validation of MTHC model was based on hydropower generation on a country level. Data used to validate hydropower generation was obtained from the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency platform [32]. Model results, as well as compared values from ENTSO-E can be seen in **Table 4**. Subsequent to model validation, model was solved for the additional wet and dry years with a change in water inflow inputs.

Yearly aggregated hydropower generation for the Balkan Region averaged at 145.91, 175.48 and 232.18 GWh/day, while it peaked at 236.06, 277.96 and 331.86 GWh/day for dry, average and wet year, respectively. Minimum hydropower generation values were 88.66, 89.92 and 135.02 GWh/day for the dry, average and wet year, respectively. Annual region aggregated hydropower generation from MTHC model shows increase from 53 258 GWh for dry year to 64 050 and 84 747 GWh for the average and wet year, respectively.

Table 4. MTHC hydropower generation for the reference/average (2015) year

Country	**MTHC model [GWh]**	**ENTSO-E [GWh]**	**Δ/ENTSO-E [%]**
Albania	5696	/	/
Bosnia and Herzegovina	5614	5650	-0.64
Bulgaria	5963	6155	-3.12
Croatia	5719	5657	1.10
Greece	6278	6091	3.06
Hungary	237	227	4.51
Kosovo	141	/	/
Montenegro	1442	1415	1.90

North Macedonia	1585	1514	4.71
Romania	16 849	16 545	1.84
Serbia	10 532	10 633	-0.95
Slovenia	3997	4060	-1.56
Sum	64 053	57 947	0.46

Region aggregated run-of-river hydropower generation on a daily time scale can be seen in **Figure 4**. Annual region aggregated run-of-river hydropower generation averaged at values of 59.17, 65.86 and 80 GWh/day for dry, average and wet year, respectively. Run-of-river hydropower generation peaked at values of 86.19, 87.07 and 101.73 GWh/day, while the minimum reached was 40.88, 43.18 and 51.52 GWh/day, for a dry, average and wet year, respectively.

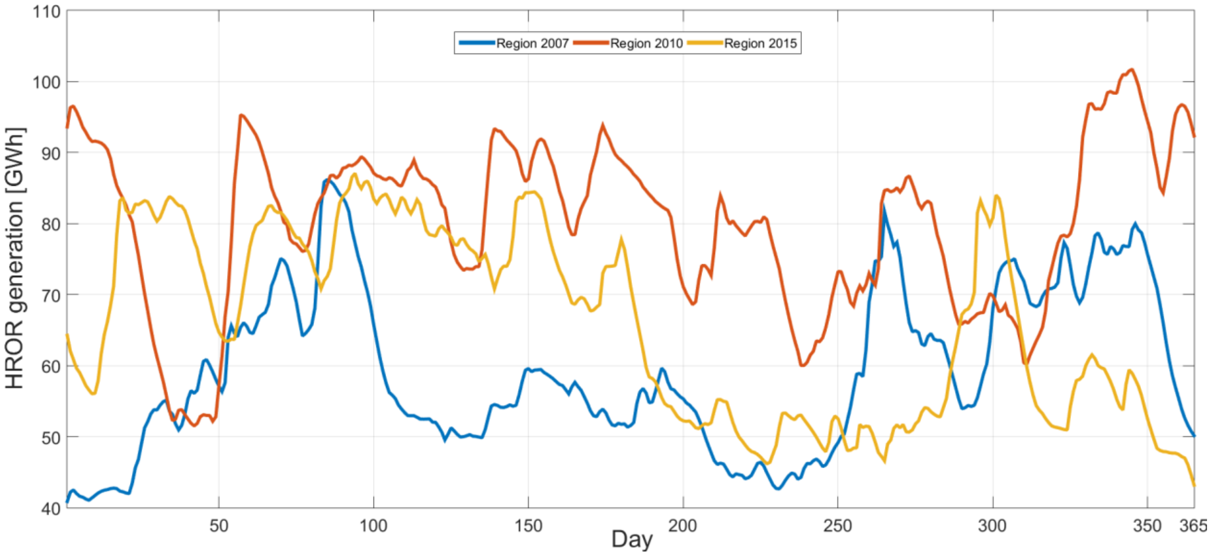

Figure 4. Region aggregated run-of-river hydropower generation for dry (2007), average (2015) and wet (2010) year, in GWh

4.2. Dispa-SET Unit Commitment and Dispatch model results

Dispa-SET UCD model was run for the three different hydrological years using hourly time step. MTHC model results in form of run-of-river hydropower generation and reservoir levels were used as an input for the different scenario models in Dispa-SET UCD.

Table 5. Region aggregated results for a dry (2007), average (2015) and wet (2010) year

Region aggregated statistics	Unit	Dry	Average	Wet
Average electricity cost	€/MWh	17.79	16.35	14.05
Total consumption	TWh	289.22	289.22	289.22
Total system cost	m EUR	4978	4573	3932
Peak load	GW	47.992	47.992	47.992
Net imports	TWh	9.452	9.452	9.452
NUC generation	TWh	48.356	48.356	48.356
LIG generation	TWh	151.33	140.15	125.12
HRD generation	TWh	3.506	3.072	2.430
GAS generation	TWh	6.244	4.682	1.462
WST generation	TWh	0.090	0.090	0.090
SUN generation	TWh	6.919	6.919	6.919
WIN generation	TWh	10.272	10.272	10.272
WAT generation	TWh	53.064	65.237	85.132
CO_2 emissions	$MtCO_2$	164.36	152.67	133.96

Difference in average electricity cost between dry and average year is due to the lower amount of energy generated from hard coal (decrease from 3.51 TWh for dry year, to 3.07 TWh for average year), lignite (decrease from 151.33 TWh for dry year, to 140.15 TWh for average year) and gas-powered units (decrease from 6.24 TWh for dry year, to 4.68 TWh for average year), which is replaced with hydropower generation (increase from 53.06 TWh for dry year, to 65.24 TWh for average year). Similar scenario can be observed when comparing average and wet years. One can say that drop in average electricity price from 16.35 €/MWh to 14.05 €/MWh can be explained by decrease in electricity generation from hard coal (decrease from 3.07 TWh for average year, to 2.43 TWh for wet year), lignite (decrease from 140.15 TWh for average year, to 125.12 TWh for wet year) and gas-fired units (decrease from 4.68 TWh for average year, to 1.46 TWh for wet year), at the expense of increased hydropower generation (increase from 65.24 TWh for average year, to 85.13 TWh for wet year). Similarly, drop in CO_2 emissions from dry to wet year, due to decrease in fossil-fuel generation, and increase in hydropower generation, can be seen in **Table 5**. Wind and solar generation is the same across the simulated years, because of the same capacity factor being used as an input data.

Table 6. Dispa-SET UCD hydropower generation for the reference/average (2015) year

Country	UCD model [GWh]	ENTSO-E [GWh]	Δ/ENTSO-E [%]
Albania	5907	/	/
Bosnia and Herzegovina	5664	5650	0.24
Bulgaria	6392	6155	3.85
Croatia	6069	5657	7.27
Greece	6288	6099	3.09
Hungary	247	227	8.62
Kosovo	144	/	/
Montenegro	1515	1415	7.04
North Macedonia	1855	1514	22.55

Romania	16 149	16 545	-2.40
Serbia	10 919	10 633	2.69
Slovenia	4090	4060	0.75
Sum	65 237	57 955	2.12

Compared results on hydropower generation on a country level can be seen in **Table 6**. Table shows that modelled results are closely following statistically obtained data from ENTSO-E, with difference on region level being only 2.12%. Highest difference between modelled results and statistical data are for countries Croatia, Hungary and North Macedonia, with differences of 7.27, 8.62 and 22.55%, respectively. Even though 22.55% difference for North Macedonia is high, modelled results are close to the IEA statistical data, with the difference of only -0.51%. IAE statistical obtained data for Croatian hydropower generation is 6556 GWh, which with ENTSO-E data gives average vale for hydropower generation of 6107 GWh. Comparing that results with modelled hydropower generation for Croatia gives only -0.62% difference. Higher percentage difference for a Hungary can be explained with total smaller amount of hydropower production which in turn gives higher percentages with smaller offsets from statistical data. Pumped storage hydropower units account for 6.88, 6.04 and 9.41 TWh of hydropower generation for average, dry and wet year, respectively. When expressed in percentages, pumped-storage hydropower generation accounts for 10.5, 11.4 and 11% of total hydropower generation for average, dry and wet year, respectively. Hydropower generation as Dispa-SET UCD model result can be seen in **Figure 5**.

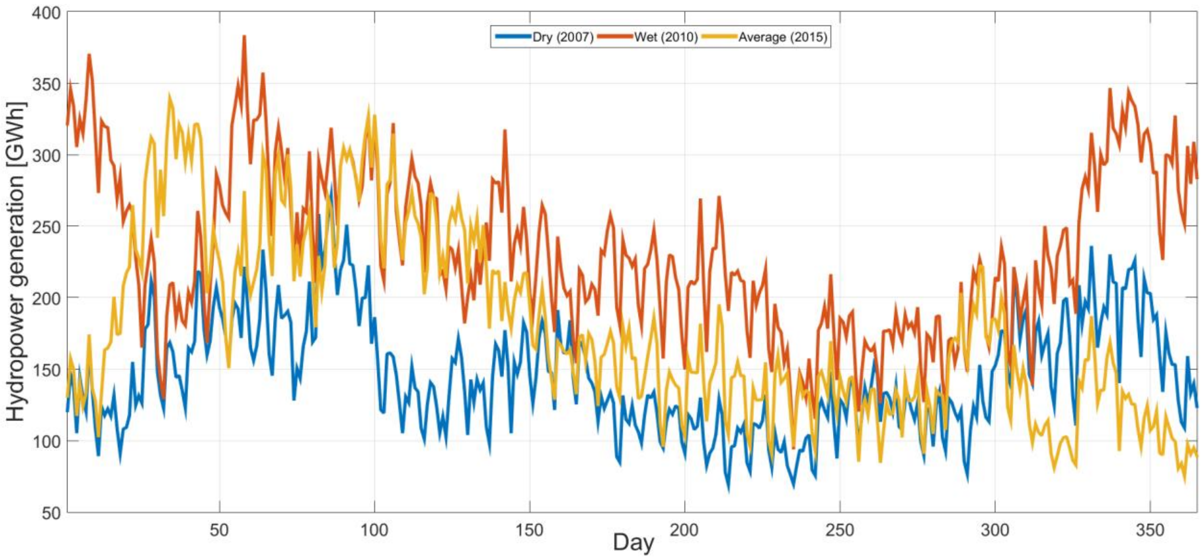

Figure 5. Dispa-SET UCD region aggregated hydropower generation for dry (2007), average (2015) and wet (2010) year

5. Conclusion

This study shows successful implementation of two energy models and hydrological LISFLOOD model for detailed analysis of impacts on the regional power system for different hydrological conditions. Countries included in the study are six Western Balkan countries, Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, Serbia, and neighbouring countries Bulgaria, Croatia, Greece, Hungary, Romania and Slovenia. Combining water inflows from hydrological LISFLOOD model with two energy models, three different scenarios for dry, average and wet year were conducted.

Besides power generation, results from UCD model include economical, commitment and power dispatch values for each unit and can be aggregated by country or region. Results show an increase of hydropower generation from 53.06 GWh for dry year, to 65.24 and 85.13 GWh for average and wet year, respectively. Increase in hydropower generation is at expense of a decrease in fossil-fuel power generation. Furthermore, average electricity cost decreased from 17.79 €/MWh for the dry year to 16.35 and 14.05 €/MWh for an average and wet year, respectively.

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