# Primjena Dispa-SET modela na analizu spone vodnih i elektroenergetskih sustava u zemljama Zapadnog Balkana i susjedstva

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# MASTER'S THESIS

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# Applying the Dispa-SET model to the analysis of the water-power nexus in the Western Balkans and neighbouring countries

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I hereby declare that this thesis is entirely the result of my own work and knowledge obtained during my studies, except where otherwise indicated. I have fully cited all used sources and I have only used the ones given in the list of references.

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# NOMENCLATURE

| **Symbol** | **Unit** | **Description** |
|---|---|---|
| p | - | Time periods |
| ut | - | Thermal power plants |
| ur | - | Renewable power plants: 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 [75] |
| 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* |
| dt | h | Period duration |
| Gravity | $m/s^2$ | Gravity constant |
| Density | $kg/m^3$ | Water density |
| Factor 1 | $Mm^3/(m^3 \cdot s)$ | Conversion factor from $m^3/s$ to $Mm^3$ |
| Factor 2 | $GWh/((m^3/s) \cdot m)$ | Conversion factor from $m^3/s$ to GWh |
| Technology (*u*,*t*) | / | Technology [75] |
| 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 |
| f | - | Fuel types |
| h | - | Hours |
| i | - | Time step in the current optimization horizon |
| l | - | Transmission lines between nodes |
| mk | - | {DA: Day-Ahead, 2U: Reserve up, 2D: Reserve down} |
| n | - | Zones within each country (currently one node per country) |
| p | - | Pollutants |
| t | - | Power generation technologies |
| tr | - | Renewable power generation technologies |
| u | - | Units |
| s(*u*) | - | Storage units (including hydro reservoirs) |
| chp(*u*) | - | CHP units |
| AvailabilityFactor(u,i) | % | Percentage of nominal capacity available |
| CHPPowerLossFactor(u) | % | Power loss when generating heat |
| CHPPoweToHeat(u) | % | Nominal power-to-heat ratio |
| CHPMaxHeat(chp) | MW | Maximum heat capacity of CHP plant |
| CHPType | / | CHP Type |
| CommittedInitial(u) | / | Initial commitment status |
| CostFixed(u) | €/h | Fixed cost |
| CostLoadShedding(n,h) | €/MWh | Shedding cost |
| CostRampDown(u) | €/MW | Ramp-down cost |

| | | |
|---|---|---|
| CostRampUp(u) | €/MW | Ramp-up cost |
| CostShutDown(u) | €/u | Shut-down costs for one unit |
| CostStartUp(u) | €/u | Start-up cost for one unit |
| CostVariableH(u,i) | €/MWh | Variable cost |
| CostHeatSlach(chp,h) | €/MWh | Cost of supplying heat via other means |
| Curtailment(n) | / | Curtailment |
| Demand(mk,n,i) | MW | Hourly demand in each zone |
| Efficiency(u) | % | Power plant efficiency |
| EmissionMaximum(n,p) | €/tP | Emission limit per zone for pollutant p |
| EmissionRate(n,p) | tP/MW | Emission rate of pollutant p from unit u |
| Fuel(u,f) | / | Fuel type used by unit u |
| HeatDemand(chp,h) | MWh/u | Heat demand profile for CHP units |
| K_QuickStart(n) | / | Reserve that can be provided by offline units |
| LineNode(l,n) | / | Line-zone incidence matrix |
| LoadShedding(n,h) | MW | Load that may be shed per zone in 1 hour |
| Location(u,n) | / | Location |
| Nunits(u) | / | Number of units inside the cluster |
| OutageFactor(u,h) | % | Outage factor per hour |
| PartLoadMin(u) | % | Percentage of minimum nominal capacity |
| PowerCapacity(u) | MW/u | Installed capacity |
| PowerInitial(u) | MW/u | Power output before initial period |
| PowerMinStable(u) | MW/u | Minimum power for stable generation |
| PowerMustRun(u) | MW | Minimum power output |
| PriceTransmission(l,h) | €/MWh | Price of transmission between zones |
| QuickStartPower(u,h) | MW/h/u | Available max capacity for tertiary reserve |
| RampDownMaximum(u) | MW/h/u | Ramp down limit |
| RampShutDownMaximum(u) | MW/h/u | Shut-down ramp limit |
| RampStartUpMaximum(u) | MW/h/u | Start-up ramp limit |
| RampUpMaximum(u) | MW/h/u | Ramp up limit |
| Reserve(t) | / | Reserve provider |
| StorageCapacity(s) | MWh/u | Storage capacity |
| StorageChargingCapacity(s) | MW/u | Maximum charging capacity |
| StorageChargingEfficiency(s) | % | Charging efficiency |
| StorageDischargeEfficiency(s) | % | Discharge efficiency |

| | | |
|---|---|---|
| StorageInflow(s,h) | MWh/u | Storage inflows |
| StorageInitial(s) | MWh | Storage level before initial period |
| StorageMinimum(s) | MWh/u | Minimum storage level |
| StorageOutflow(s,h) | MWh/u | Storage outflows |
| StorageProfile(u,h) | MWh | Storage long-term profile |
| Technology(u,t) | / | Technology type |
| TimeDownMinimum(u) | h | Minimum down time |
| TimeUpMinimum(u) | H | Minimum up time |
| VOLL() | €/MWh | Value of lost load |
| Committed(u,h) | - | Unit committed at hour h |
| CostStartUpH(u,h) | € | Cost of start up |
| CostShutDownH(u,h) | € | Cost of shutting down |
| CostRampUpH(u,h) | € | Ramping cost |
| CostRampDownH(u,h) | € | Ramping cost |
| CurtailedPower(n,h) | MW | Curtailed power at node n |
| Flow(l,h) | MW | Flow through lines |
| Heat(chp,h) | MW | Heat output by CHP plant |
| HeatSlack(chp,h) | MW | Heat satisfied by other sources |
| Power(u,h) | MW | Power output |
| PowerMaximum(u,h) | MW | Power output |
| PowerMinimum(u,h) | MW | Power output |
| Reserve_2U(u,h) | MW | Spinning reserve up |
| Reserve_2D(u,h) | MW | Spinning reserve down |
| Reserve_3U(u,h) | MW | Non spinning quick start reserve up |
| ShedLoad(n,h) | MW | Shed load |
| StorageInputs(s,h) | MWh | Charging input for storage units |
| StorageLevel(s,h) | MWh | Storage level of charge |
| Spillage(s,h) | MWh | Spillage from water reservoirs |
| SystemCost(h) | € | Total system cost |
| LL_MaxPower(n,h) | MW | Deficit in term of maximum power |
| LL_RampUp(u,h) | MW | Deficit in term of ramping up for each plant |
| LL_RampDown(u,h) | MW | Deficit in term of ramping down |
| LL_MinPower(n,h) | MW | Power exceeding the demand |
| LL_2U(n,h) | MW | Deficit in reserve up |
| LL_3U(n,h) | MW | Deficit in reserve up – non spinning |
| LL_2D(n,h) | MW | Deficit in reserve down |
| AL | - | Albania |

| | | |
|---|---|---|
| BA | - | Bosnia and Herzegovina |
| EL | - | Greece |
| HR | - | Croatia |
| ME | - | Montenegro |
| MK | - | North Macedonia |
| RS | - | Serbia |
| SI | - | Slovenia |
| XK | - | Kosovo |
| BG | - | Bulgaria |
| RO | - | Romania |
| IT | - | Italy |
| AT | - | Austria |
| HU | - | Hungary |
| UA | - | Ukraine |
| TR | - | Turkey |
| BIO | - | Bagasse, Biodiesel, Gas From Biomass, Gasification, Biomass, Briquettes, Cattle Residues, Rice Hulls Or Padi Husk, Straw, Wood Gas (From Wood Gasification), Wood Waste Liquids Excl Blk Liq (Incl Red Liquor, Sludge, Wood,Spent Sulfite Liquor And Oth Liquids, Wood And Wood Waste |
| GAS | - | Blast Furnace Gas, Boiler Natural Gas, Butane, Coal Bed Methane, Coke Oven Gas, Flare Gas, Gas (Generic), Methane, Mine Gas, Natural Gas, Propane, Refinery Gas, Sour Gas, Synthetic Natural Gas, Top Gas, Voc Gas & Vapor, Waste Gas, WellheadGas |
| GEO | - | Geothermal steam |
| HRD | - | Anthracite, Other Anthracite, Bituminous Coal, Coker By-Product, Coal Gas (From Coal Gasification), Coke, Coal (Generic), Coal-Oil Mixture, Other Coal, Coal And Pet Coke Mi, Coal Tar Oil, Anthracite Coal Waste, Coal-Water Mixture, Gob, Hard Coal / Anthracite, Imported Coal, Other Solids, Soft Coal, Anthracite Silt, Steam Coal, |

| | | |
|---|---|---|
| | | Subbituminous, Pelletized Synthetic Fuel From Coal, Bituminous Coal Waste) |
| HYD | - | Hydrogen |
| LIG | - | Lignite black, Lignite brown, Lignite |
| NUC | - | U, Pu |
| OIL | - | Crude Oil, Distillate Oil, Diesel Fuel, No. 1 Fuel Oil, No. 2 Fuel Oil, No. 3 Fuel Oil, No. 4 Fuel Oil, No. 5 Fuel Oil, No. 6 Fuel Oil, Furnace Fuel, Gas Oil, Gasoline, Heavy Oil Mixture, Jet Fuel, Kerosene, Light Fuel Oil, Liquefied Propane Gas, Methanol, Naphtha, ,Gas From Fuel Oil Gasification, Fuel Oil, Other Liquid, Orimulsion, Petroleum Coke, Petroleum Coke Synthetic Gas, Black Liquor, Residual Oils, Re-Refined Motor Oil, Oil Shale, Tar, Topped Crude Oil, Waste Oil |
| PEA | - | Peat Moss |
| SUN | - | Solar energy |
| WAT | - | Hydro energy |
| WIN | - | Wind energy |
| WST | - | Digester Gas (Sewage Sludge Gas), Gas From Refuse Gasification, Hazardous Waste, Industrial Waste, Landfill Gas, Poultry Litter, Manure, Medical Waste, Refused Derived Fuel, Refuse, Waste Paper And Waste Plastic, Refinery Waste, Tires, Agricultural Waste, Waste Coal, Waste Water Sludge, Waste |
| COMC | - | Combined cycle |
| GTUR | - | Gas turbine |
| HDAM | - | Conventional hydro dam |
| HROR | - | Hydro run-of-river |
| HPHS | - | Pumped hydro storage |
| ICEN | - | Internal combustion engine |
| PHOT | - | Solar photovoltaic |
| STUR | - | Steam turbine |
| WTOF | - | Offshore wind turbine |
| WTON | - | Onshore wind turbine |

| | | |
|---|---|---|
| CAES | - | Compressed air energy storage |
| BATS | - | Stationary batteries |
| BEVS | - | Battery-powered electric vehicles |
| THMS | - | Thermal storage |
| P2GS | - | Power-to-gas storage |
| HE | - | Hydropower plant |
| TE | - | Thermal power plant |
| KTE | - | Combined cycle |
| RHE | - | Pumped hydro storage |
| CHP | - | Pumped hydro storage |
| Unit | - | Unit name |
| Year | - | Commissioning year |
| Technology | - | Technology |
| Primary fuel | - | Fuel |
| Zone | - | Zone |
| PowerCapacity | MW | Capacity |
| Efficiency | % | Efficiency |
| MinEfficiency | % | Efficiency at minimum load |
| CO2Intensity | $TCO_2$/MWh | $CO_2$ intensity |
| PartLoadMin | % | Minimum load |
| RampUpRate | %/min | Ramp up rate |
| RampDownRate | %/min | Ramp down rate |
| StartUpTime | h | Start-up time |
| MinUpTime | h | Minimum up time |
| MinDownTime | h | Minimum down time |
| NoLoadCost | €/h | No load cost |
| StartUpCost | € | Start-up cost |
| RampingCost | €/MW | Ramping cost |
| CHP | y/n | Presence of CHP |
| STOCapacity | MWh | Storage capacity |
| STOSelfDischarge | %/h | Self-discharge rate |
| STOMaxChargingPower | MW | Maximum charging power |
| STOChargingEfficiency | % | Charging efficiency |
| CHPType | Extraction/back-pressure/p2h | CHP Type |
| CHPPowerToHeat | - | Power-to-heat ratio |
| CHPPowerLossFactor | - | Power loss factor |
| CHPMaxHeat | MW(th) | Maximum heat production |
| STOCapacity | MWh(th) | Capacity of heat storage |
| STOSelfDischarge | % | % of storage heat loss pet |

| | | |
|---|---|---|
| IEA | - | International Energy Agency |
| ENTSO-E | - | European Network of Transmission System Operators for Electricity |

# ABSTRACT

This study describes the implementation of three different models for detailed analysis of impacts on the regional power system for different hydrological years. The region includes countries Slovenia, Croatia, Serbia, Bosnia and Herzegovina, Montenegro, Kosovo, North Macedonia, Albania and Greece. Combining the hydrological LISFLOOD model with Dispa-SET models for simulation of the regional power system, three scenarios for dry, average and wet year were studied to investigate the regional power system output for different hydrological conditions. The first part of the study included gathering data needed for detailed representation of regional power system participants and analysis of data from the LISFLOOD model provided by the European Commission’s Joint Research Centre (JRC).

Data on regional power systems were obtained from available databases and documentation published by regional TSO’s. Details on region hydrology and power system of each country is described in the first two sections. Three mentioned models are in more detail described in Section 3. The LISFLOOD model is included in the study in the form of its results that are needed as input data for Dispa-SET models. Water inflows are crucial for a successful run of Dispa-SET models that can be divided into Dispa-SET Medium-Term Hydrothermal Coordination model (Dispa-SET MTHC) and Dispa-SET Unit Commitment and Dispatch model (Dispa-SET UCD). Dispa-SET MTHC model is used to in detail represent hydropower generation of each unit included in the study. Results in the form of hydropower generation for run-of-river units and reservoir levels of hydropower units with accumulations are used as input data for Dispa-SET UCD model. Besides power generation, results from UCD model include economical, commitment and power dispatch values for each unit and aggregated by country or region.

The model was validated based on the hydropower generation for the reference year (2015). Results on three different hydrological years, 2007, 2015 and 2010 used as dry, average and wet year, respectively, are shown in Section 6. Region hydropower generation was compared to available statistical data from ENTSO-E and International Energy Agency. The study shows model results on power system operation for different hydrological conditions.

KEYWORDS: LISFLOOD, Dispa-SET, Balkan Peninsula, Water-power nexus, Water-energy nexus

# SAŽETAK

U ovom radu proučava se poveznica između tri postojeća modela. U svrhu energetskog modeliranja i prikaza rezultata za različite ulazne podatke stvara se poveznica između LISFLOOD hidrološkog modela i Dispa-SET modela koji simulira energetski sustav definirane regije. Odabrano simulirano područje obuhvaća zemlje Zapadnog Balkana, Srbija, Bosna i Hercegovina, Sjeverna Makedonija, Crna Gora, Albanija, Kosovo, te tri susjedne države, Hrvatska, Slovenija i Grčka. U sklopu zadatka bilo je potrebno pokazati poveznicu između hidrologije i energetskog sustava promatranog područja.

Cjelokupni model sastoji se od tri povezana modela. LISFLOOD model je hidrološki model koji se koristi za simuliranje hidrologije i/ili poplava na određenom području, a u sklopu ovog rada koristi se u obliku ulaznih podataka vezani na protoke rijeka i padalinama na definiranim područjima. Protoci rijeka i padaline potrebni su kao ulazni podaci za proizvodnju hidroelektrana u Dispa-SET modelu. Dispa-SET model može se podijeliti na dva zasebna modela. Prvi model je Dispa-SET Medium-Term Hydrothermal Coordination (Dispa-SET MTHC) model koji se na kratkoročnoj razini, u ovome radu na razini jedne godine uz vremenski korak od jednog dana, koristi za izračun proizvodnje protočnih hidroelektrana i razine vode hidroelektrana koje koriste akumulacije. U Dispa-SET MTHC modelu detaljno se definiraju tehnički podaci za pojedinu hidroelektranu dok su ostale proizvodne jedinice definirane uz osnovne tehničke značajke. Rezultati Dispa-SET MTHC modela i podaci dobiveni iz LISFLOOD modela koriste se kao ulazni podaci za Dispa-SET Unit Commitment and Dispatch (Dispa-SET UCD) model u kojem se detaljno definiraju tehnički podaci za pojedinu elektranu vezano na njenu fleksibilnosti i cjelokupnu proizvodnju u definiranom energetskom sektoru. Rezultati Dipsa-SET UCD modela daju detaljan prikaz rada pojedinog postrojenja i njihove isplativosti kao i ekonomske pokazatelje cjelokupne regije.

U sklopu rada prikazan je utjecaj različitih hidroloških godina na energetski sustav promatranog područja koji je definiran u sklopu pojma poveznice hidrologije i proizvodnje energije. (eng. water-power nexus, water-energy nexus)

KLJUČNE RIJEČI: LISFLOOD, Dispa-SET, Balkanski poluotok, Energetsko planiranje, Water-power poveznica, Water-energy poveznica

# PROŠIRENI SAŽETAK (EXTENDED SUMMARY IN CROATIAN)

U svrhu istraživanja utjecaja hidrologije na energetski sustav promatrane regije pristupilo se modeliranju uz primjenu tri postojeća modela. Odabrano simulirano područje obuhvaća zemlje Zapadnog Balkana, Srbija, Bosna i Hercegovina, Sjeverna Makedonija, Crna Gora, Albanija, Kosovo, te tri susjedne države, Hrvatska, Slovenija i Grčka. U sklopu rada koristili su se modeli, ili njihovi rezultati, kako bi se pokazala poveznica između hidrologije i rada energetskog sektora regije. (eng. water-power nexus, water-energy nexus).

Prije definiranja modela koji se koriste u sklopu ovog rada, navedeni su podaci o hidrologiji i energetskom sustavu promatranog područja. Podaci o hidrologiji definirani su u drugom poglavlju, dok su podaci o energetskom sustavu regije pobliže objašnjeni u trećem poglavlju.

Porječje cijele regije podijeljeno je na dva glavna sliva, Crnomorski i Sredozemni. Sredozemni sliv se daljnje može podijeliti na Jadranski, Jonski i Egejski sliv. Pobliže su objašnjene značajke pojedinih slivova i pripadajućih rijeka.

U trećem poglavlju detaljnije je definirana struktura proizvodnje električne energije iz različitih izvora za svaku državu obuhvaćenu ovim radom. Naveden je popis elektrana s podacima o nominalnoj snazi, tehnologiji i gorivu koji se koristi za proizvodnju električne energije.

U četvrtom poglavlju objašnjava se pojedini model korišten u ovome radu. Korišteni modeli obuhvaćaju hidrološki model LISFLOOD [71], te Dispa-SET modele koji se mogu podijeliti na Dispa-SET Medium-Term Hydrothermal Coordination (Dispa-SET MTHC) i Dispa-SET Unit Commitment and Dispatch (Dispa-SET UCD)..[73],[77]

Hidrološki model LISFLOOD koristi za simuliranje hidrologije i/ili poplava na određenom području, a u sklopu ovog rada koristi se u obliku ulaznih podataka vezani na protoke rijeka i padalina na definiranim područjima. Kako model nije javno dostupan, već je kreiran za korištenje unutar grupe koja radi na projektu prirodnih katastrofa u sklopu Zajedničkog Istraživačkog Centra (eng. Joint Research Centre - JRC), u sklopu ovog rada ne koristi se u modeliranju sustava, već se samo njegovi rezultati, u obliku protoka rijeka i padalina, koriste kao ulazni podaci za Dispa-SET modele. Navedeni podaci dostavljeni su od strane JRC-a za definirane elektrane u sklopu energetskog sustava promatranog područja.

Navedeni protoci rijeka i padalina potrebni su kao ulazni podaci za Dispa-SET modele kako bi se mogla definirati proizvodnja energije iz hidroelektrana.

Dispa-SET MTHC model na kratkoročnoj razini, u ovome radu na razini jedne godine uz vremenski korak od jednog dana, koristi se za izračun proizvodnje protočnih hidroelektrana i razine vode hidroelektrana koje koriste akumulacije. Spomenuti podaci potrebni su kao ulazni podaci za Dispa-SET UCD model. U sklopu Dispa-SET MTHC modela, detaljnije se definiraju tehnički podaci za hidroelektrane, jer je primaran rezultat njihova proizvodnja, dok su podaci o ostalim elektranama svedeni na osnovne tehničke značajke. Model je definiran kao problem linearnog programiranja gdje je cilj funkciju cilja svesti na minimum. Funkcija cilja sastoji se od varijabilnih troškova proizvodnje električne energije, troškova pumpanja vode za reverzibilne hidroelektrane, troškova preljeva, prijenosa energije, rasterećenja te troškova ne proizvodnje iz obnovljivih izvora. Ograničenja u obliku jednadžbi i nejednadžbi definiraju rad tržišta, granice proizvodnje električne energije, proizvodnju energije iz vjetra i sunca, prijenos energije te detalje oko bilance vodnih resursa i proizvodnje energije iz hidroelektrana. Dobiveni rezultati o proizvodnji protočnih hidroelektrana i razini vode u akumulacijama prenose se u Dispa-SET UCD model.

Dispa-SET UCD model simulira kratkoročni rad energetskog sustava, u ovome radu na godišnjoj razini sa satnim vremenskim korakom, s ciljem dobivanja rezultata o detaljnom načinu rada pojedinih postrojenja. Model se može predstaviti kao problem linearnog programiranja ili problem mješovitog linearnog programiranja, ovisno o ulaznim podacima. Model se optimizira minimizirajući funkciju cilja koja definira ukupni trošak rada energetskog sustava promatranog područja. Funkcija cilja sastoji se od troškova pokretanja i gašenja postrojenja, troškova promjena izlazne snage postrojenja, troškova prijenosa energije, troškova rasterećenja sustava te varijabilnih i fiksnih troškova proizvodnje električne energije. Dodatne jednadžbe i nejednadžbe definiraju rad tržišta, pomoćnih usluga, skladištenje energije, proizvodnju topline, emitirane emisije $CO_2$, prijenos energije, rasterećenje sustava te smanjenje rada obnovljivih izvora energije.

U petom poglavlju definiraju se ulazni podaci za navedene Dispa-SET modele.

Kako se Dispa-SET MTHC značajnije odnosi na rad hidroelektrana, odabran je pristup gdje su ostali tipovi postrojenja spojeni u grupe temeljene na vrsti goriva. Tako se svaka država sastoji od, u modelu definiranih, hidroelektrana i virtualnih elektrana temeljeno na vrsti goriva koju koriste za proizvodnju električne energije. Navedeni popis elektrana odnosi se na referentnu 2015. godinu. U poglavlju se može pronaći detaljniji opis hidroelektrana s podacima o instaliranoj snazi, protoku, padu i akumulaciji. U poglavlju se nalaze i ostali ulazni podaci koji obuhvaćaju potrošnju električne energije za svaku državu, protoke rijeka i padalina dobivene iz LISFLOOD modela, profile rada vjetro i solarnih elektrana, kapaciteti prijenosne mreže, topologija koja definira mrežu hidroelektrana te detaljniji ulazni podaci vezani uz rad hidroelektrana. U nastavku su objašnjeni ulazni podaci specifični za Dispa-SET UCD model.

U šestom poglavlju prikazani su rezultati simulacija. Kako je u sklopu zadatka bilo potrebno pokazati utjecaj različitih hidrologija za promatrani energetski sustav, odabrane su tri godine gdje svaka predstavlja jedan od scenarija s različitim hidrološkim uvjetima. Bazirano na podacima o protocima rijeka i padalinama, odabrane su godine s maksimalnim, minimalnim te prosječnim iznosom padalina. Kao kišna godina odabrana je 2010., kao sušna 2007, te kao prosječna godina 2015. Provedene su simulacije u Dispa-SET MTHC, te su prikazani rezultati za sve tri godine. Prikazani rezultati obuhvaćaju podatke o proizvodnji električne energije iz hidroelektrana, razina vode u rezervoarima akumulacija, te proizvodnja protočnih hidroelektrana. Proizvodnja hidroelektrana uspoređena je sa stvarnom proizvodnjom za referentnu, 2015. godinu. Na kraju je prikazana proizvodnja električne energije agregirana po gorivima za sve tri godine, gdje se može vidjeti utjecaj promjene proizvodnje električne energije iz hidroelektrana i ukupni utjecaj na cijeli energetski sustav.

Dobiveni rezultati iz MTHC modela koriste se kao ulazni podaci za Dispa-SET UCD model. Primarni razlog primjene MTHC modela je dobiti rezultate u obliku razina vode u akumulacijama hidroelektrana. Potreba za time proizlazi iz UCD modela. UCD model ima vremenski korak od jednog sata, te kako bi se smanjilo računalno vrijeme simulacije, modeliranju se nije pristupilo tako da se prati jedna simulacija na razini cijele godine, već se pristupilo postupku razdjeljivanja perioda od jedne godine na korisnički definiran broj optimizacijskih koraka koji se rješavaju rekurzivno. Zbog tog pristupa model ima tendenciju isprazniti svu akumulaciju hidroelektrana na kraju jednog optimizacijskog koraka, stoga je kao ulazni podatak potrebno definirati razinu akumulacija za svaku pojedinu hidroelektranu na satnoj razini. Prikazani su rezultati o ekonomičnosti sustava, ukupnoj proizvodnji agregirano prema gorivu te broj paljenja i gašenja svih postrojenja. Slikovito i tablično detaljnije su prikazani rezultati o proizvodnji iz hidroelektrana za sve tri godine. Prikazana je i krivulja proizvodnje iz hidroelektrana gdje je usporedno prikazana i proizvodnja dobivena iz statističkih podataka. U konačnici su slikovito, u prilogu ovog rada, prikazani podaci o razini vode u akumulacijama i podaci o radu pojedinog postrojenja za svaku državu zasebno. Iz dobivenih rezultata definirani su zaključci o utjecaju hidrologije na rad promatranog elektroenergetskog sustava te su navedene smjernice za budući rad kojim bi se još detaljnije prikazao spomenuti utjecaj, s namjerom proširenja regije na Mađarsku, Bugarsku i Rumunjsku.

# 1. INTRODUCTION

Power generation sector worldwide accounts for high water withdrawal and consumption due to the hydropower generation and cooling of thermal power plants. The operation of the power generation sector is constrained by availability of the water resources which are needed for energy generation in hydropower plants and for proper cooling of thermal power plants, but the water resources are also used for a variety of purposes not related to the power sector, such as irrigation, flood control, water supply, agriculture etc.[1],[2]

According to the International Commission on Large Dams database, irrigation is the most common purpose of use of water reservoirs while hydropower generation represents the second largest use of single-purpose dams, followed by water supply. Multipurpose dams are mostly used for flood control and water supply.[1]

As stated in [2], in the past decade there have been several examples of issues related to the shortage of water resources or high river water temperatures needed for proper cooling of thermal power plants. Mostly due to the joint effects of heat waves and/or bad hydrological conditions of the main river channels, consequences of curtailment of nuclear power in France with a cost of €300 million in 2003 have been experienced. 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. This events bring demand restrictions, monetary losses and increased wear of the thermal power plants.[2],[3],[4],[5]

Mentioned impacts on the power system with forecasts that climate change will cause a number of similar events to rise, raise the questions on have to implement better water management.[2]

The term water-energy nexus (or water-power nexus) is used to refer the interactions between the water and energy sectors for the best utilization of water resources. Mentioned water-energy link is discussed within the WATERFLEX project carried out by C7 (Knowledge for the Energy Union) and D2 (Water and Marine resources) of the European Commission’s Joint Research Centre with its main goal to incorporate hydropower production as a source of flexibility for the European power system.[2]

The hydropower is a recognized technology that provides benefits for the total power system operation. Spinning reserve, black start capability, frequency response, flexibility and reserve with quick start and shutdown capabilities, identify hydropower as a main cost-competitive resource for integration of variable renewable sources into the European power system.[1],[2] Even though the importance of water-energy nexus is recognized as a new challenge for better control of water resources, current power system models overlook water-related constraints as contributions to power system 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]

To better represent and analyse water-power nexus, the method proposed in the WATERFLEX project consist of combining the LISFLOOD hydrological model [7], Dispa-SET Unit Commitment and Dispatch model (Dispa-SET UCD)[8] and the Dispa – SET Medium-Term Hydrothermal Coordination model (Dispa-SET MTHC)[9].

The MTHC model determines reservoir levels of the hydropower plants during a certain period of time, which is then passed as an input data to the Dispa-SET UCD model. The Dispa-SET UCD model establishes schedule operations and dispatch, as well as the economic results related to power generation. More on the model formulation will be discussed in the Section 4.[2]

### 1.1. Climate change and hydropower production

The ambitious protection targets have been adopted by the European Union to help fight climate change. Targets were adopted in October 2014, updated in 2016 with Winter Package and revised in 2018 stating that goals of, at least 40% cuts in green gas emissions over pre-industrial level, at least 32% share for renewable energy in gross final energy consumption and at least 32.5% improvement in energy efficiency must be met. The long-term strategy tends to transform EU into a competitive low-carbon economy with setting goals to achieve an 80-95% reduction of GHG emission by 2050. To achieve this goal, the EU must rely on investments in low-carbon technologies, increase energy efficiency, use of renewable energy and deployment of smart grid infrastructure. As of today, more than half GHG emissions come from the developing countries, which set the EU to lead the international effort for the UN global climate agreement, which has been adopted at the Climate Change Conference in Paris. Its main goal is to keep the global temperature rise well below 2 °C to pre-industrial levels with ambitions strive to keep it below 1.5 °C.[10]

A case study conducted at four hydropower plants included in [11] provides conclusions:

- Impacts of climate change are related to direct effects on the hydropower generation potential, that being river flow, but also indirectly through an increase in general demand for energy due to higher summer and lower winter temperatures.[10],[11]

- A decrease in river flow would affect power generation for all types of hydropower plants but the highest effect would be on run-of-river hydropower plants.[10],[11]
- With the increase in temperature, the evaporation rate of the reservoirs would affect hydropower production of the facilities with smaller reservoirs that have a high storage area to volume ratio. Other types of hydropower plants would experience the same effect, but in a smaller amount in total hydropower production decrease.[10],[11]
- With higher runoffs in the autumn/winter and lower in spring/summer, high impact on the overall decrease of hydropower production of run-of-river hydropower plants and hydropower plants with small storage would be experienced.[10],[11]

Overall, it is to assume that, due to the future extreme droughts in summer and floods in the autumn/winter, an adaptation of hydropower plants to the climate change relies on better management of water reservoirs. The reservoirs should be managed and sized to compensate for the increase in seasonal runoffs.[10]

Balkan Peninsula countries are among some of the most water-rich countries in Europe with the amount of water available per person of 10,600 $m^3$/cap.[10] Water resources have always been important for the Balkan Peninsula economy with its use for irrigation, industry, drinking water supply, tourism, livestock production and hydropower production. The hydropower electricity production accounts for 49% of all electricity generated in the Western Balkan region.[10]

The Balkan Peninsula is getting warmer and projections are that the trend will continue with the expected increase in global temperatures. 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. The projections in [12] state that if the worst case scenario happens, that being the rise of the 4 °C, the 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 sources, reduction in water availability would strongly affect the regions power system, with projections that the hydropower potential in Croatia could decrease up to 35 %. Also, 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.[10], [12]

Overall can be stated that the reduction of hydropower potential will happen in the future, but the loss could be compensated by better reservoir management.[10]

## 1.2. Literature review

For the past decade, water-power nexus has been a popular research topic. In [4] the International Energy Agency brought the question on the dependence of energy on water and vice versa with the topic being more discussed in [13]. In 2014, the US Department of Energy published the report “The Water-Energy Nexus: Challenges and Opportunities”.[14] Security of sustainable electricity supply in cooperation with the water management was discussed in the [15]. The cooperation between the US Department of Energy, European Commission’s Joint Research Centre and the Directorate-General for Research and Innovation organized a workshop for better integration of water and power system.[16]

The water-power nexus has been studied in Europe for the Greek power system.[2] The Greek case study analyses the implications of water on the power system and vice versa for three different historical scenarios. Also, the water stress index is defined to determine the locations and time periods with high possibilities of water shortages for the dry hydrological year. The same problem was discussed for the Iberian Peninsula region in [17]. Additionally, the vulnerability analysis of cooling-related constraints on maximum allowable water withdrawal has been conducted for coal-fired power plants with high marginal cost and moderate installed capacity, and nuclear power plant with low marginal cost and high installed capacity. More studies for the Europe region can be found in [18] – [23]. For the US region, the water-power nexus is discussed in [24] and [25]. The analysis was carried out to research the water-energy nexus for states Texas and Illinois. In [24] the analysis of 2011 droughts was studied to examine the power plant’s vulnerability regarding moderate year 2010. In [25] the economic implications were studied for shifting from coal to natural gas, and replacement of open-loop with the closed-loop cooling technologies. The report for the Middle East and North Africa is represented in [26], while the Western Africa region is discussed in [6]. In [26] MENA region was analysed that is composed of 20 countries spanning from Iran to Morocco. 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 included region. In [6] the model was created to determine economic impacts, the water consumption and withdrawal, and detailed operation of the power system under different current and future assumptions. In this report, additional improvements were mentioned for the more accurate representation of water-energy nexus.[17]

# 2. DRAINAGE BASINS OVERVIEW

As previously stated, the study includes six Western Balkan countries, Serbia, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, Albania, and additional neighboring countries, Slovenia, Croatia and Greece. In the next few subchapters, hydrology of major river basins will be explained. The Balkan Peninsula drainage basin can be divided into two main drainage basins. The Black Sea drainage basin and Mediterranean Sea drainage basin. Mediterranean drainage basin can be further divided into Adriatic Sea drainage basin, Aegean Sea drainage basin and Ionian Sea drainage basin. Figure 1. represents two main drainage basins while the black dashed line shows the border between them.[27]


**Figure 2.1. Two main drainage basins of the Balkan Peninsula [27]**

## 2.1. Black Sea Drainage Basin

The major rivers and tributaries are Danube, Inn, Morava, Vah, Drava, Tisza, Sava, Velika Morava, Olt, Siret and Prut.[28] Danube, Sava, Drava, Krka, Una, Vrbas, Bosna, Drina and Velika Morava Rivers are included in this study since they flow through mentioned countries.[29]


**Figure 2.2. Danube River Basin District Overview [29]**

### 2.1.1. *Danube River Basin*

The Danube represents the second largest river in Europe with its flow distance of 2,826 km. It flows through 19 countries and drains an area of around 800,000 km$^2$ and its average altitude is 458 m. The main Danube tributaries are Leitha, Raab, Drava, Sava and Velika Morava Rivers.[10]

Because of its size, west to east flow orientation, and diverse relief, there are big differences in climate between Lower and Upper Danube. Atlantic climate has an influence on the Upper Danube where winters are mild and precipitations are higher, while the Lower Danube exhibits lower precipitations, dry and cold winters due to the influence of eastern continental regions. Parts of the Drava and Sava Rivers are affected by a Mediterranean climate. Highest precipitations are in the higher parts of the Alps (~3200 mm) while the lowest precipitations are in the Black Sea and delta regions (~350 mm). Average peak precipitation for the western part of the basin happens in July, for the southeast parts it peaks in February/March, while it peaks at autumn months for the areas influenced by the Mediterranean climate. Middle and Lower Danube have highest average annual temperatures of around 11-12 °C, while seasonal differences increase from west to east. For example, the seasonal temperature difference in Hungary can be as high as 74°C.[28]

Due to the spatial differences in precipitation, there is a strong effect on the surface run-off and most of the flow comes from the Austrian and Romanian mountains (around 40%). The average annual specific discharge decreases from 25-35 L/s/km$^2$ in Alpine mountains to 19 L/s/km$^2$ for the Sava, 6.3 L/s/km$^2$ for the Tisza and to 2.8 L/s/km$^2$ for the rivers of eastern Carpathian region. Iron Gate dams and larger water management schemes along the Prut, Siret, Arges and Olt Rivers modified the flow regime of the Lower Danube.[28] The list of the hydropower plants in the Danube River Basin can be seen in documents [30] and [32].

**Table 2.1. Flow regime of the Danube River and its tributaries [28]**

| River | Station | Catchment area [km$^2$] | Mean annual discharge [m$^3$/s] |
|---|---|---|---|
| Danube | Berg | 4,047 | 38.5 |
| Danube | Vienna | 101,731 | 1,920 |
| Danube | Ceatal Izmail | 807,000 | 6,486 |
| Inn | Passau-Ingling | 26,084 | 732 |
| Morava | Moravsky Jan | 24,129 | 110 |
| Vah | Sala | 10,620 | 138 |
| Drava | Donji Miholjac | 37,142 | 541 |
| Tisza | Senta | 141,715 | 792 |
| Sava | Sremska Mitrovica | 87,996 | 1,527 |
| Velika Morava | Ljubicevski most | 37,320 | 277 |
| Olt | Stoenesti | 22,683 | 172 |
| Siret | Lungoci | 36,036 | 210 |
| Prut | Cernicvi | 6,890 | 67 |

#### 2.1.2. *Sava River Basin*

River Sava, with its flow length of 945 km represents the largest Danube tributary by volume and the second largest by catchment area (95,793 km$^2$). The Sava basin is international basin covering six countries, 40% in Bosnia and Herzegovina, 26% in Croatia, 15.4% in Serbia, 11% in Slovenia, 7.5% in Montenegro and 0.1% in Albania.[10] The Sava's watershed covers 45 to 70% of the surface area of the Slovenia, Bosnia and Herzegovina, Croatia and Montenegro and its water resources represent almost 80% of the freshwater resources of mentioned four countries. [30] Around 8.8 million people live in the Sava River basin with cities like Belgrade, Zagreb, Sarajevo, Ljubljana and Banja Luka being the largest cities on the Sava River or its tributaries.[10]

The Sava River is formed out of headwaters of Dolinka Sava and the Bohinjka Sava from the Lake Bohinj. Its river bed passes through Slovenia and Croatia where it continues along the border of Croatia and Bosnia and Herzegovina, from the confluence of the Una River and almost to the confluence of the Drina River. In Serbia, it remains a lowland river with wide channel and it enters the Danube River in Belgrade.[28]

The Sava is under influence of Alpine and Mediterranean climates with an average annual air temperature of 9.2 °C and average annual precipitation of 1,000 mm. In the upper Kupa region and in the Julian Alps, maximum precipitation reaches around 3,800 mm, while the minimum precipitation of around 600 mm is reached in the Pannonian Plain. Average annual discharge is 1,572 $m^3/s$, while its largest tributary, the Drina River, has a discharge of 370 $m^3/s$. The Sava contributes for 25% of the total Danube discharge.[28]

Major Sava tributaries are rivers Kupa, Una, Vrbas, Bosna and Drina.[28]

The Kupa River is tributary of the Sava and it forms a natural border between Croatia and Slovenia. It originates in Croatia in the mountain region of Gorski Kotar. Before it reaches the Slovenian border it receives inflow from small Čabranka River. It receives inflow from the Lahinja River before eventually detaching from the Slovenian border. The river then reaches the city of Karlovac where it receives inflow from the Dobra and Korana Rivers. Before it reaches the city of Sisak and enters the Sava River, it merges with the Glina and Odra Rivers.[31]

The Una sub-river basin has an area of 10,816 $km^2$. The length of the river is 214 km and it forms part of the border between Croatia and Bosnia and Herzegovina. The climate is continental with annual precipitation of around 900 mm. The spring is in Croatia and after 12 km of flow, it enters mountains in northwestern Bosnia and Herzegovina, while proceeding to the Una Sana Canton. The confluence is in Croatia near Jasenovac.[30]

The Vrbas sub-river basin has an area of 6,386 $km^2$ and it is the smallest Sava River tributary in BiH. The spring is in the Vranica mountain.[30]

The Bosna sub-river basin has a catchment area of 10,457 $km^2$ and it is the second biggest tributary of the Sava River in Bosnia and Herzegovina. The spring is located in Sarajevsko polje, in the Igman Mountain.[30]

The Drina sub-river basin is the largest tributary of the Sava River. It is 346 km long and the catchment area is 19,570 km$^2$. The catchment is shared between BiH, Serbia, Albania and Montenegro. The river is composed of the Piva and Tara Rivers which flow from Montenegro. The list of the hydropower plants in the Sava River Basin can be seen in document [30] and [32].


**Figure 2.3. The Sava River Basin with tributaries [30]**

### 2.1.3. *Velika Morava River Basin*

The Velika Morava is the large right-bank tributary of the lower Danube, upstream of the Iron Gate dams. It drains around 40% of the Serbian territory with a catchment area of around 38,000 km$^2$. The catchment is located in some parts of Bulgarian territory (~3%) as well as parts of North Macedonia and Montenegro. Its average channel width is 140 m and the average water depth of 1-4 m.[28]

Main tributaries are Crnica, Jovanovačka Reka, Ravanica, Resava and Resavica on the right side, and Jasenica, Rača, Lepenica, Belica River, Lugomir and Kalenićka Reka on the left side. Before it reaches the Danube, the Velika Morava River splits, while creating 47 km long arm called Jezava. From the left side, it is joined by the Ralja River and it flows into Danube River.[30]

The Velika Morava, with its length of 185 km, starts at the confluence of the South and the West Morava near the small town of Stolać. The West Morava branch is the longest tributary with the length of 493 km and its longest water source of the Ibar River. The Ibar River is the longest tributary of the West Morava which gives the Ibar-West Morava-Velika Morava river system a length of 550 km, being the longest waterway in the Balkan Peninsula.[28],[30]

The South Morava drains southeast Serbian territory with the catchment area of a 15,446 km$^2$. The rivers two biggest headwaters originate from the Rilo-Rhodope and North Macedonian-Serbian Mountains. Its largest tributary is the Nišava River with the length of 218 km and catchment area of a 4,068 km$^2$. The source of the Nišava River is located in southern slopes of the Stara Planina Mountains in Bulgaria. It merges the South Morava near the city of Niš.[28]

The West Morava drains southwest Serbian territory with the catchment area of a 15,567 km$^2$. Its headwater sources are located in Golija, Mučanj and Tara Mountains in the Dinaric Alps. The headwaters merge near the village Leposavić. The biggest tributary of the West Morava is the Ibar River with its source in eastern Montenegro. It merges with West Morava near the city of Kraljevo.[28]

The climate of the Velika Morava River is mostly continental with average annual temperatures of 11-12 °C. Precipitation is highest in May and June while being the lowest in February and October. Average discharge is 277 m$^3$/s and it peaks during the snowmelt period in springtime.[28]

The first major hydro water activities started between 1960 and 1995 on the whole Velika Morava River Basin. The river directions were shortened, meander has been cut off and the swamp areas have been transformed into fish ponds. Extensive drainage system has been carried out to increase the proportion of arable land. Multiple dams and water reservoirs have been built to be used for hydropower generation, municipal water supply, irrigation and flood protection.[28] The list of the hydropower plants in the Velika Morava River Basin can be seen in document [30] and [32].

### 2.1.4. *Drava River Basin*

The Drava River is the 4th largest and the 4th longest Danube tributary with its catchment area of a 40,087 km$^2$ and the length of the 719 km. It is shared by Italy, Austria, Slovenia, Hungary and Croatia. The main tributaries are the Austrian rivers Isel, Moll, Lieser and Gurk and the Mura River that reaches the Drava River at Croatian-Hungarian border. Drava merges with the Danube near the city of Osijek and basin is inhabited by approximately 3.6 million people. The largest cities on the Drava River are Graz, Maribor and Osijek.[28]

The Drava River source is located in the Southern Alps in Italy near Dobbiaco. For its first few kilometers of flow, it drops 400 m in altitude, while entering Austria. It flows through Eastern Tyrol and Carinthia, while separating the central Alps from the limestone Alps. The Drava then continues through northeast Slovenia and enters Croatia.[28]

There are 23 installed hydropower plants in the upper region, upstream of the Mura confluence, numbering the 12 power station in Austria, 8 in Slovenia and 3 in Croatia.(Figure 2.4.) Also, there are 26 hydropower plants along the Mura River. Downstream of the Mura confluence the river is not suitable for effective hydropower production and river continues forming Croatian-Hungarian border for 145 km. The confluence of the Drava river forms Kopački Rit Nature Park.[28]

The climate is mild continental and partly humid with an average temperature of 10.9 °C. The average rainfall is between 600-750 mm. The highest flow occurs in May and June because of the Alpine snowmelt period. There is a second peak of flow in late autumn due to high precipitation in the Southeast Alps. The lowest flow regime is experienced in May and June. Due to the high precipitation in the upper basin, the Drava River has high flood risk in the upper part of the river but the flood is prevented with the construction of dams and reservoirs. Average discharge of the Drava River is 541 m$^3$/s.[28]

Human activities resulted in significant changes on the hydrological regime. The Drava River is regulated since the past century, but there are some semi-natural parts of the basin in the lower parts. The upper part hydropower regime causes major water level changes, which impact the flora and fauna.[28]

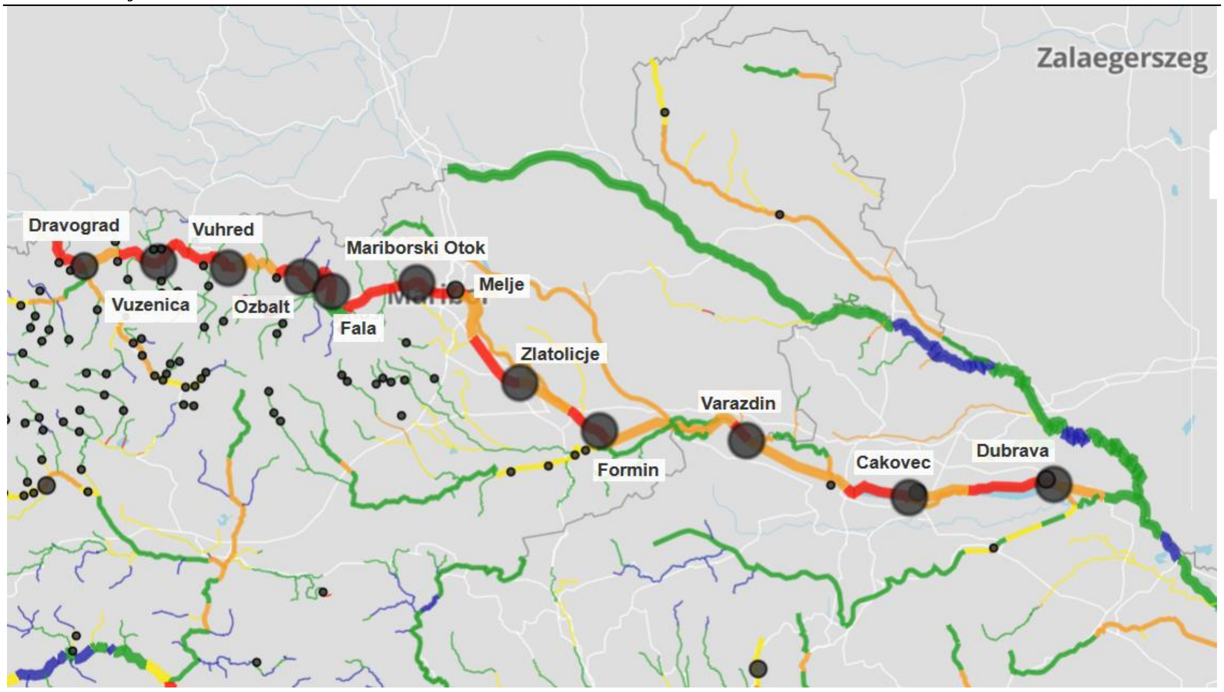



**Figure 2.4. Part of the Drava River and the hydropower plants located in Slovenia and Croatia [32]**

## 2.2. Adriatic Sea Drainage Basin

The analysis of the Adriatic Sea Drainage Basin will cover rivers Neretva, Trebišnjica, Morača, Drin, Bune, Mat, Seman and Vjose/Aoos, Cetina, Krka, Zrmanja and Isonzo/Soča.[30]

### 2.2.1. *Neretva-Trebišnjica River Basin*

The catchment area of the Neretva-Trebišnjica River Basin is 10,380 km$^2$ and it is shared between Croatia and Bosnia and Herzegovina. The total length of the Neretva River is 230 km, of which 208 km are in Bosnia and Herzegovina territory and 22 km in Croatian territory. The rivers source is in the Bosnia and Herzegovina at the base of the Zelengora Mountain and it enters southern Croatia forming delta with an area of 200 km$^2$. The Neretva River is the largest karstic river in the Dinaric Mountains and it is also hydrologically connected with the Trebišnjica River.[30],[33]

The Neretva River experience high annual precipitation, but its flow is lost in the underground and the karstic springs that have substantial contribution to the surface flow. The maximum runoff occurs in December and the minimum in the July/August. Jablanica, Rama, Grabovica, Salakovac and Mostar are five hydropower plants located in Bosnia and Herzegovina that utilize the flow of the Neretva River.[33]

The Neretva-Trebišnjica River Basin has a crucial socio-economic role in energy production, drinking water supply and agricultural use.[30]

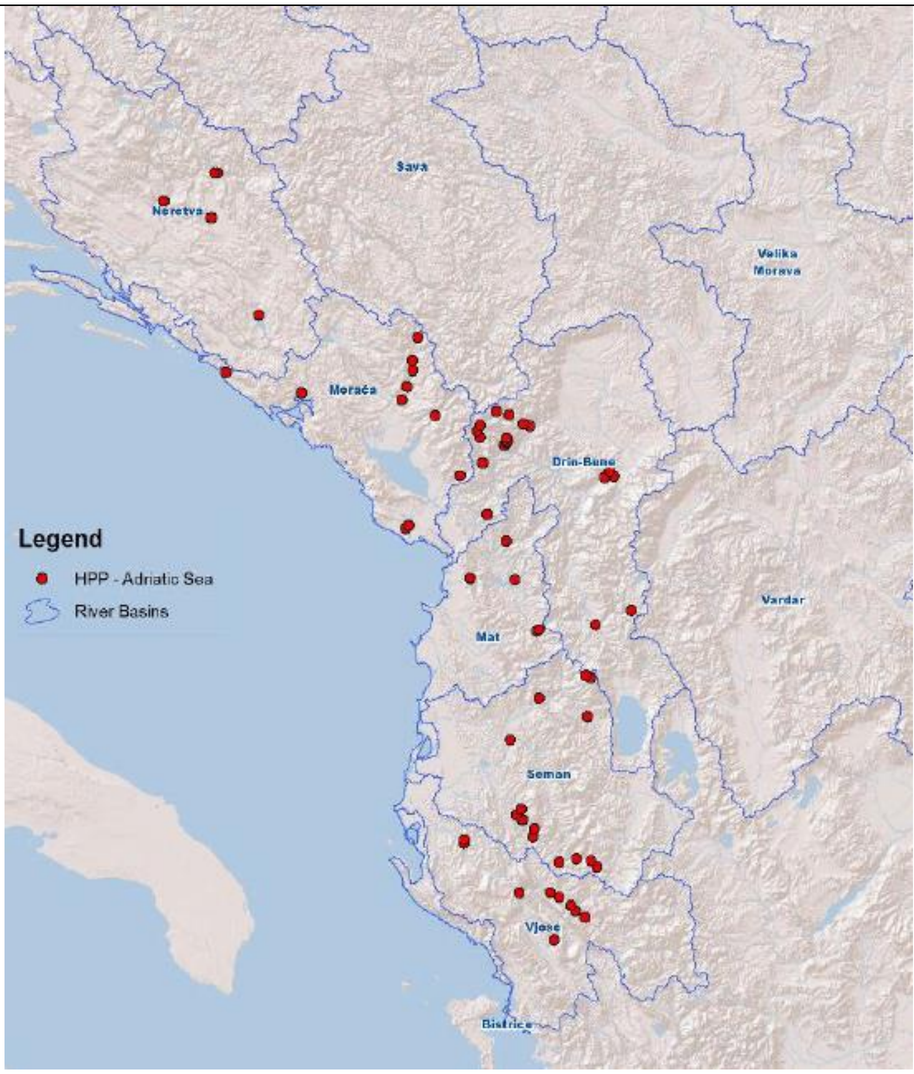



**Figure 2.5. River basins of the Adriatic Sea Drainage Basin with locations of HPP [30]**

### 2.2.2. *Morača River Basin*

The Morača River springs in northern Montenegro under the Rzača Mountain. The main tributaries are the Koštanica, Sjevernica, Javorski Potok, Trnovačka Rijeka, Slatina, Ibrištica, Ratnja and Požanjski Potok. It generally flows southwards for around 113 km before emptying in the Skadar Lake. On its northern part, the Morača River is fast mountain river. Its biggest tributary is the Zeta River, which merges with Morača River north of the city of Podgorica.[30]

### 2.2.3. *Drin-Bune River Basin*

The Drin River is the largest Albanian river and it is the third greatest river discharge in the European Mediterranean. The Drin River catchment area is 14,173 $m^2$ with a length of a 285 km. The river is composed of the two main river branches, the White Drin and the Black Drin. The White Drin drains Serbia and Montenegro and the Black Drin originates from the Lake Pespa and the Lake Ohrid. The Buna River merges with the Drin River before they enter the Adriatic Sea. The Buna River drains the Shkodra Lake.[30],[33] The Black Drin River is transboundary river since it flows from its source in North Macedonia to a downstream country Albania and merges with the White Drin near the city of Kukes. The total length of the river is 149 km. With the main purpose of hydropower production, there are two dams with their associated reservoirs with a total installed power of 126 MW. The Black Drin River has a catchment area of a 3,350 km$^2$ with average annual precipitation of 993 mm. Its average annual discharge is 52 m$^3$/s.[30]

The main tributary of the Black Drin River is the Radika River which is formed by a number of small springs in the area of Shara and Korab mountains. The catchment area of the Radika River is around 880 km$^2$ while its average annual flow is approximately 30 m$^3$/s. Its main tributaries are Mavrovksa, Ribnica and Mala Reka Rivers.[30]

### 2.2.4. *Mat River Basin*

The catchment area of the Mat River is 2,441 km$^2$ and the total length is 115 km. It springs in Diber County near Martanesh. It passes cities Klos and Burrel and after 10 km flows into a large Ulez Lake. Downstream of the Ulez Lake it enters the smaller Shkopet Lake and forms gorge through the mountain. It enters the Adriatic Sea near Fushe-Kuqe, close to the cities of Lezhe and Lac.[30]

### 2.2.5. *Seman River Basin*

The Seman River is the second longest river in Albania with the catchment area of a 5,649 km$^2$ and a length of 281 km. It is composed of the two rivers in the Berat County, near the village of Kozare. Osum and Devoll Rivers, after merging, pass along the Fier County where the Gjanica River joins in and they enter the Adriatic Sea, south of the lagoon of Karavasta. Precipitation is scarce with annually averaging to 1,084 mm. Its average annual flow is 95.7 m$^3$/s. The average temperature of the water ranges from 6.8 °C in January up to 25.5°C in August.[30]

### 2.2.6. *Vjose/Aoos River Basin*

The Vjose/Aoos River flows through the northwest part of Greece before it enters Albania. Its largest tributary is Drino River with a catchment area of 1,320 km$^2$.[17]

The Vjose/Aoos flow length is 272 km with 86 km of flow being in Greece. The catchment of the entire Vjose/Aoos River Basin is around 6,700 km$^2$. Its highest discharge is in winter months, up to 400 m$^3$/s, while the lowest river flow occurs during the month from July to October. The most of its catchment area is in its natural form with restricted agriculture, forestry, cattle breeding and aquaculture.[30],[33]

### 2.2.7. *Cetina River Basin*

The Cetina River is the 101 km long river in southern Croatia with a catchment area of a 1,463 km$^2$. It springs in the northwestern slopes of the Dinara Mountain from the multiple springs near the village Cetina, 7 km north of the small town Vrlika. The large Peruća Lake is located near the town Vrlika created by the Peruća Dam. Cetina River then passes to the lower Sinj karst field, passing through the city of Sinj. Passing the city of Sinj, the river continues eastwards through the city of Trilj, before it continues to the westward around the Mosor Mountain. Then it flows into the Adriatic Sea in the city of Omiš. The main tributaries of the Cetina River Basin are rivers Rumin, Kosinac, Ruda, Dragović, Dabar, Vojskova and Karakašica.[34]

The flow of the Cetina River is regulated by means of the hydropower plants operation. The hydropower plants located on the Cetina River are HE Peruca, HE Orlovac, HE Dale, HE Kraljevac and HE Zakucac.[32],[34]

### 2.2.8. *The Krka River Basin*

The Krka River is 73 km long, located in Croatia's Dalmatia County with its catchment area of 2,088 km$^2$. The river springs at the foot of the Dinara Mountain, near the border between Croatia and Bosnia and Herzegovina. The river flows through the Krčić Canyon before it enters the karst valley of Knin, where its tributaries Kosovčica, Orašnica and Butižnica merge with the river. The river then passed to the Brljansko Lake, while further downstream, river forms the Visovačko Lake. The 7 km long Visovačko Lake ends at the confluence of the Krka River and its largest tributary, the Čikola River. Downstream of the mentioned confluence, the river flows past the town of Skradin, before it forms Prokljasko Lake together with its tributary, the Gudača River. At the last, the river empties into the Bay of Šibenik to the Adriatic Sea.[35]

Hydropower plants located on the Cetina River are HE Jaruga, HE Miljacka and three small hydropower plants HE Golubić, mHE Roški Slap and mHE Krčić.[32],[35]

### 2.2.9. *The Zrmanja River Basin*

The Zrmanja River is the 69 km long river in the southern Lika and northern Dalmatia County and its catchment area is a 907 km$^2$. The river spring is located in the southern part of the Lika County, under the southern peak of the Pljesevica Mountain called Postak. It flows southward through the narrow and long valley before it turns westwards reaching the town of Obrovac. Few kilometers downstream, the river enters the Adriatic Sea at the Novigradsko More Bay. Its main tributary is the Krupa River.[36]

### 2.2.10. *The Soča/Isonzo River Basin*

The Soča River is the 138 km long river that flows through northeastern Italy and western Slovenia. Its catchment area is 3,400 km$^2$ and it springs in the Julian Alps, in the Trenta Valley at an elevation of 876 m. The river flow passes the tows of Bovec, Kobarid, Tolmin, Kanal ob Soči, Nova Gorica and Gorizia, before it enters the Adriatic Sea near the town of Manfalcone.[37]

The course of the Soča River can be divided into Upper and Medium Soča Valley and the lower Soča. The Upper Soča Valley flow is natural and its located between the rivers source and the village of Most na Soči. In the Medium Soča Valley river flow is regulated by means of three dams and accumulating lakes for the purposes of the hydropower generation of the HE Plave, RHE Avche, HE Doblar and HE Solkan hydropower plants. The lower Soča in its span from Italian-Slovenian border to its mouth is the free flowing river.[32],[38]

## 2.3. Aegean Sea Drainage Basin

The analysis of the Aegean Sea Drainage Basin will cover rivers Evros, Nestos, Strymon, Axios/Vardar, Aliakmon, Pinios, Sperchios and Evrotas.[33]

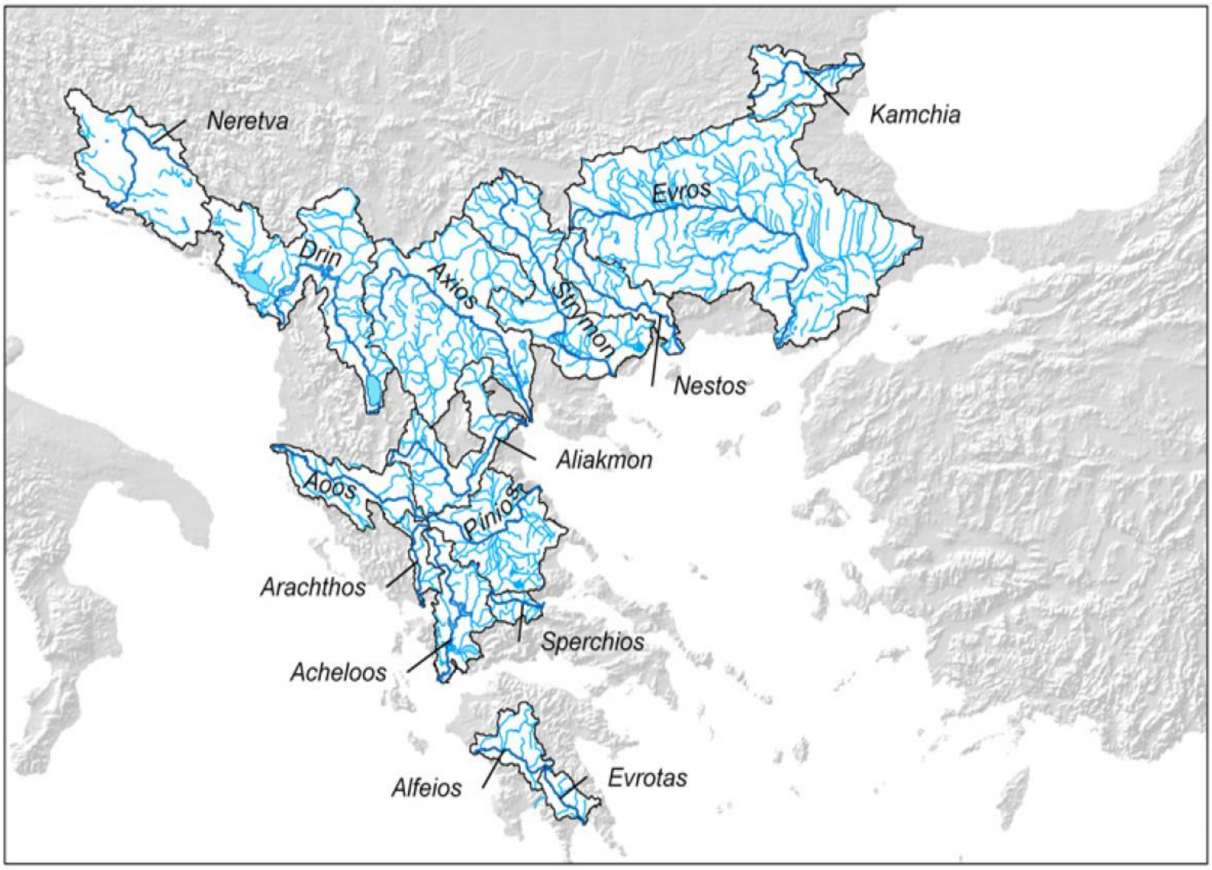



**Figure 2.6. Rivers of the South Balkan region [33]**

### 2.3.1. *Evros River Basin*

The Evos River Basin is a large river basin shared between Greece, Turkey and Bulgaria, with the percentage of its catchment area being 66.4% in Bulgarian, 27.2% in Turkish and 6.4% in Greek territory. It springs in Bulgaria, forms border between Greece and Turkey and at last, forms large delta in the Aegean Sea. The main tributaries are Tundja, Arda and Ergene Rivers.[33]

The Evros River Basin numbers around 100 tributaries with a mean annual discharge of its main tributaries, Arda, Tundja and Ergene of 2.2 $km^3$, 1.08 $km^3$ and 0.87 $km^3$, respectively. Its maximum flow occurs in spring, between March and May, while the minimum is reached between July and September. Rainfall contributes to the whole discharge for around 60% depending on the region. There are 21 large scale reservoirs with a total storage of 3,440 $Mm^3$. Even though there are a large number of reservoirs, the runoff is highly variable with frequent floods.[33]

### 2.3.2. *Nestos River Basin*

The Nestos River is a highland river that springs at the eastern slope of Rila Mountain in Bulgaria. It flows through Bulgaria and Greece entering the Aegean Sea while forming a large delta. The main tributary is Dospatis River, which sinks in Bulgaria and joins Nestos River in Greece.[8]

Most of the runoff occurs from snow melting in the mountains and the rain in the lower regions. Maximum flow occurs between April and August while its minimum occurs in September. There are 6 large reservoirs on its tributaries in Bulgaria with the largest one being Dospatis reservoir with a total storage capacity of 430 $Mm^3$. In Greece, there are three large reservoirs for hydropower production, Thysavros, Temenos, Platanovrisi and a small irrigation dam Texotes.[33]

### 2.3.3. *Strymon River Basin*

The catchment area of the Strymon River Basin is located in Bulgaria, Greece, North Macedonia and Serbia, but the Bulgarian and Greek part represent 88% of the whole catchment area. Its main tributaries are rivers Strumeshnitsa, Treklyanska in Bulgaria and Aggitis River in Greece.[33]

There are 56 multi-purpose reservoirs in Bulgaria with the total storage capacity of 141 $Mm^3$. The largest ones are reservoirs Djakovo, Studena and Pchelina.[33]

### 2.3.4. *Axios/Vardar River Basin*

The Axios/Vardar River Basin is the second largest basin in the Aegean Sea Drainage. It drains 83% of North Macedonia and small parts of Greek, Serbian and Bulgarian territory. The main tributaries are Crna and Brejalinica Rivers. The river springs at the western slopes of the Crna Gora Mountain before it reaches Skopje-Veles plain where it merges with the Treska River. Tributaries Pčinja, Crna and Bregalnica join the river before it enters Greece. Together with rivers Aliakmon, Gallikos and Loudias it forms wide delta in Thermaikos Gulf.[33]

The highest flow occurs in April and minimum in August. The mean annual runoff of its main tributaries is 2.78 $km^3$. In North Macedonia, 17 large dams have been built to control floods with its total storage capacity of more than 500 $Mm^3$.[33]

### 2.3.5. *Aliakmon River Basin*

The Aliakmon River is the longest river in Greece and it receives overflow waters from Lake Kastoria. Its main tributaries are rivers Venetikos, Almopeos and Edesseos. The Venetikos Rivers joins Aliakmon River in the rivers upstream, while rivers Almopeos and Edesseos merge with Aliakmon River via long irrigation canal. Together with Axios/Vardar River, Aliakmon forms delta in the Aegean Sea.[33]

Around 70% of the river flow is modified due to large dams being built. The largest reservoirs, Sfikia, Polyfyto and Asomata, have a storage capacity of around 3 $km^3$. In the downstream part of the river, the highest discharge occurs in summer while the minimum is reached in spring.[3]

### 2.3.6. *Pinios River Basin*

The Pinios River has catchment area in vast Thessaly plain where it flows into the Thermaikos Gulf forming 69 $km^2$ radial-shaped delta. The main tributaries contributing to its discharge are rivers Titarissios, Onochonos and Enipeas. There is only one major dam on the Smokovo River tributary. [33]

### 2.3.7. *Sperchios River Basin*

The Sperchios River Basin is the smallest catchment in the Aegean Sea Drainage Basin that spring in the Tymfristos Mountain. It flows into the Aegean Sea forming a wide lobate delta. It is a mostly unregulated river with about 69% of its flow originating from snow and 19% from the rain.[33]

#### 2.3.8. *Evrotas River Basin*

The Evrotas River Basin is the basin in south Greece territory. It enters the Aegean Sea in the Laconikos Gulf. The river springs in the Taygetos Mountain and flows south to the Lanconia basin. While entering the Aegean Sea, it forms small 53 km$^2$ wide delta.[33]

Parts of the Evrotas River exhibit an intermittent flow regime and the only stable flow from its tributaries comes from the Oinous River. There is severe water abstraction for irrigation but the river is mostly unregulated. The karstic outflow and snowmelt represent the highest discharge and it reaches its peak in March.[33]

### 2.4. Ionian Sea Drainage Basin

The analysis of the Ionian Sea Drainage Basin will cover rivers Arachthos, Acheloos and Alfeios.[33]

#### 2.4.1. *Arachthos River Basin*

The Arachthos springs are located in the Tszoumerska and Lakmos Mountains. The Arachthos Rivers enters the Ionian Sea in the Amvrakikos Gulf, where together with the Louros River forms double-delta formation which extends over 350 km$^2$ creating Greece's largest coastal swamp system.[33]

The rivers discharge peaks in December-January while its minimum occurs in August. Two main reservoirs are Pournar I and Pournari II with the coverage area of a 21 km$^2$ and storage capacity of around 800 Mm$^3$. Reservoirs, besides being used for hydropower production, also decrease seasonal flow variations.[33]

#### 2.4.2. *Acheloos River Basin*

The Acheloos River drains southern Pindos mountain range and then enters Agrinio plain with an average channel width of 25 m. The snowmelt accounts for 19% and rain 71% of the total runoff. There are four large reservoirs built and they have a storage capacity of more than 6.6 km$^3$. Maximum discharge rate occurs in July and minimum in summer times.[33]

#### 2.4.3. *Alfeios River Basin*

The Alfeios River springs at the Taygetos Mountain and enters the Ionian Sea in the Kyparissiakos Gulf. Total runoff is partly supplied by karstic runoff and its two main tributaries, Ladon and Lousios contribute with 0.64 and 0.21 km$^3$/year, respectively. Its maximum discharge peaks in January, while its minimum occurs in August. Small hydropower dam, located along the Ladon River, is used for irrigation and flood control.[33]

# 3. BALKAN PENINSULA POWER SYSTEM

## 3.1. The Western Balkan Region

The power sectors of the Western Balkan countries have a large potential of bringing additional investments to diversify the supply sources with the addition of renewable energy sources and enhance energy efficiency.[10]

The region is highly dependent on the 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.[10]

The main source of the electricity generation is lignite and hydropower with Serbia, Bosnia and Herzegovina, Kosovo and North Macedonia mostly depending on lignite-fired thermal power plants while Albania has its electricity production almost 100% from hydropower.[10]

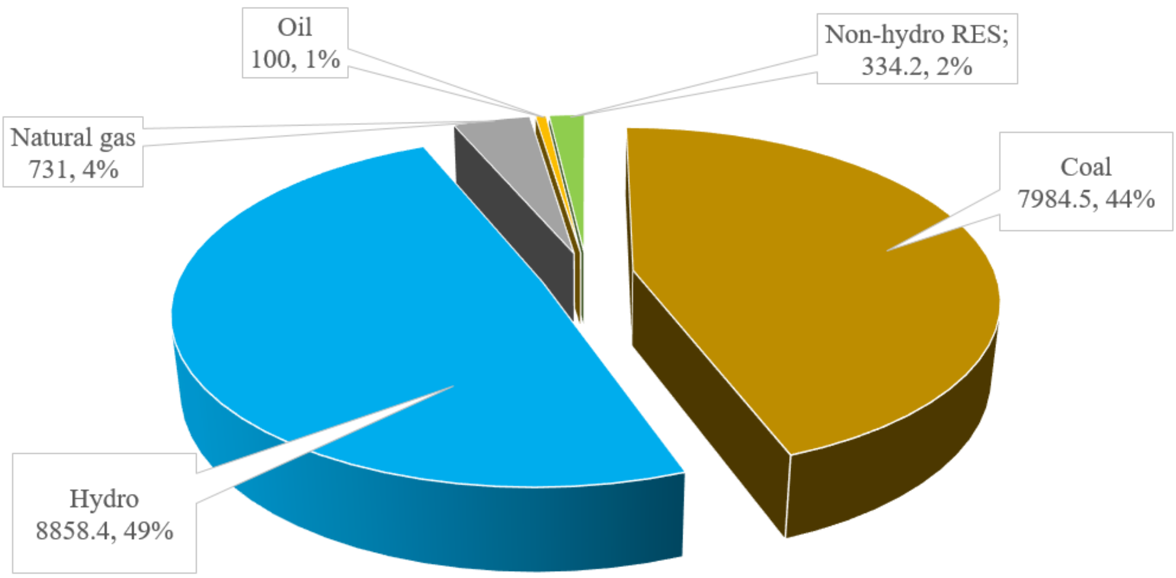



**Figure 3.1. Installed power generation capacities for WB region in 2015. (MW, %) [39]**

### 3.1.1. *Hydropower sector in the Western Balkan region*

There are 444 hydropower plants located in the WB region. There are 57 large hydropower plants (installed capacity of more than 10 MW) with most of them located in Albania and Bosnia and Herzegovina, closely followed by Serbia and North Macedonia. More data on the number of installed hydropower plants are represented in the Table. 3.1[39]

**Table 3.1. Number of hydropower plants in the Western Balkan Region [39]**

| Country | Large HPP [> 10 MW] | Small HPP [<10 MW] | Total |
|---|---|---|---|
| Albania | 17 | 137 | 154 |
| Bosnia and Herzegovina | 16 | 66 | 82 |
| Serbia | 12 | 85 | 97 |
| North Macedonia | 9 | 75 | 84 |
| Montenegro | 2 | 16 | 18 |
| Kosovo | 1 | 10 | 11 |
| Total | 57 | 389 | 446 |
| Share | 12.8% | 87.2% | 100% |

Based on the total installed capacities, the large hydropower pants account for 8,022 MW, while small hydropower plants have a capacity of 583 MW. Serbian hydropower plants account for 3,157 MW of the total WB region, followed by Bosnia and Herzegovina with 2,183 MW and Albania with installed 1,844 MW of installed hydropower capacities. Related to small hydropower plants, the most of the installed capacity is located in Albania with a total share of 43%, followed by Bosnia and Herzegovina, North Macedonia and Serbia.[39]

Even though the number of small hydropower plants represents the 87.2% in the number of facilities, they account for the smaller amount of the total installed capacity of 6.8% and an even smaller amount in the average annual hydropower generation with only 2.5%. More on the total installed capacity for the WB region in Table 3.2. Table 3.3. shows the average annual hydropower production for the period between 2001–2015.[39]

When comparing cumulative values of the hydropower capacities being installed, the 90% of the total installed capacity has been constructed and commissioned before 1990 with only 866 MW added between 1990 and 2015. During the period between 2001 and 2016, the 397 MW of the large hydropower plant capacities and 403 MW of small hydropower plants have been added.[39]

**Table 3.2. Installed hydropower capacities in the WB region, in MW [39]**

| Country | Large HPP [> 10 MW] | Small HPP [<10 MW] | Total |
|---|---|---|---|
| Albania | 1,592 | 252 | 1,844 |
| Bosnia and Herzegovina | 2,081 | 102 | 2,183 |
| Serbia | 3,092 | 66 | 3,157 |
| North Macedonia | 574 | 97 | 671 |
| Montenegro | 649 | 25 | 974 |
| Kosovo | 35 | 40 | 75 |
| Total | 8,022 | 583 | 8,605 |
| Share | 93.2% | 6.8% | 100% |

**Table 3.3. Average annual hydropower production for the period between 2001 and 2015 in GWh [39]**

| Country | Large HPP [> 10 MW] | Small HPP [<10 MW] | Total |
|---|---|---|---|
| Albania | 4,895 | 182 | 5,077 |
| Bosnia and Herzegovina | 5,572 | 97 | 5,669 |
| Serbia | 9,946 | 62 | 10,008 |
| North Macedonia | 1,273 | 194 | 1,468 |
| Montenegro | 1,722 | 33 | 1,755 |
| Kosovo | 91 | 36 | 127 |
| Total | 23,499 | 604 | 24,104 |
| Share | 97.5% | 2.5% | 100% |

### 3.1.2. *Albania*

The Albanian power generation capacities number only one thermal power plant, while the country's power generation relies on the hydropower generation with 1,838 MW of active generation capacity. The only thermal power plant, TE Vlora, is out of operation due to the technical problems or the lack of profitability. The lack of thermal power generation puts the Albanian power system in the sensitive position when dry hydrological year happens, putting the Albanian security of electricity supply to the test. To compensate for the loss of the available hydropower generation, Albania imports electricity from its neighboring countries.[39],[40]

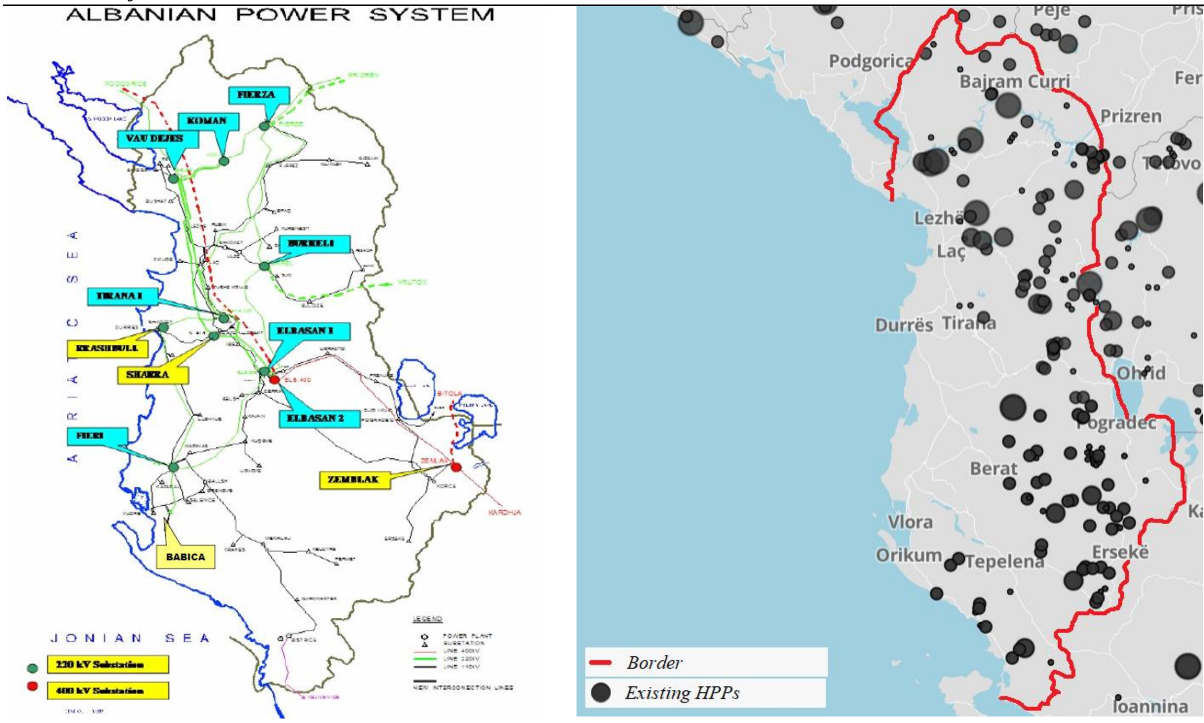



**Figure 3.2. Albanian transmission network with locations of larger power plants (left)[44]; Locations of the existing hydropower plants (right),[32]**

**Table 3.4. The list of the major power plants in the Albania [40], [41], [42], [43], [44],[45]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| TE Vlora | 98 | COMC | OIL |
| HE Fierza | 500 | HDAM | WAT |
| HE Koman | 600 | HDAM | WAT |
| HE Vau Dejes | 250 | HDAM | WAT |
| HE Shkopet | 24 | HDAM | WAT |
| HE Ulez | 25 | HDAM | WAT |
| HE Bistrica I | 22,5 | HROR | WAT |
| HE Bistrica II | 5 | HROR | WAT |
| HE Tervol | 10.6 | HROR | WAT |
| HE Arras | 4,8 | HROR | WAT |
| HE Smokthina | 9 | HROR | WAT |
| Small HPPs | 252 | HROR | WAT |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

### 3.1.3. *Bosnia and Herzegovina*

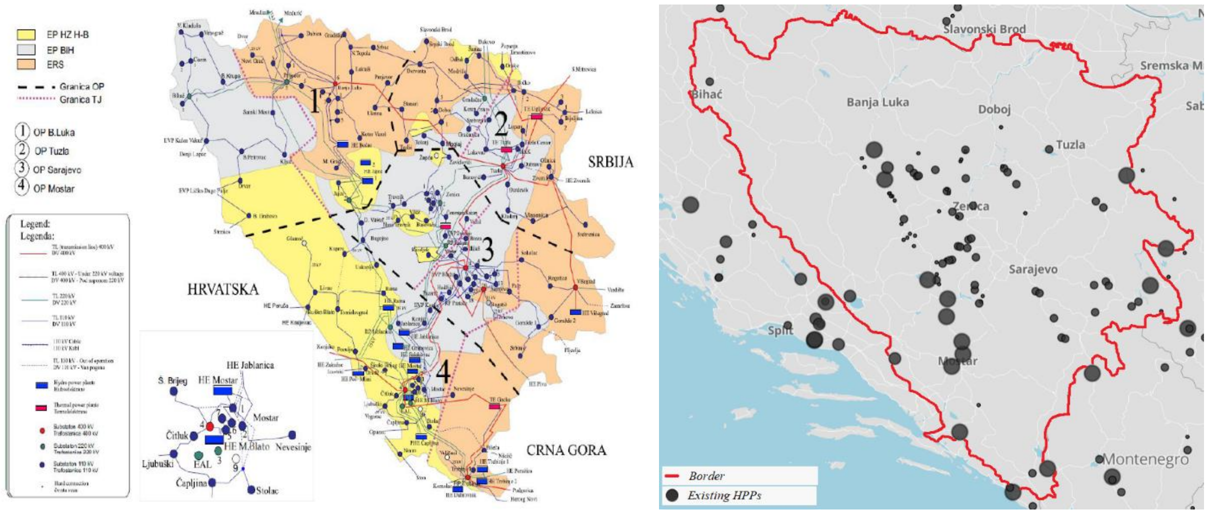



**Figure 3.3. Transmission network of Bosnia and Herzegovina with locations of larger power plants (left),[41]; Locations of existing hydropower plants (right),[32]**

The power capacities of Bosnia and Herzegovina consist of five main coal-fired power plants and a number of hydropower plants.[40]

The five thermal power plants, TE Gacko, TE Kakanj, TE Tuzla, TE Ugljevik and TE Stanari use lignite coal as an energy source and are built near the coal mines which provides them with the needed energy source. The Abid Loloc, Zenica, Kakanj and Breza mines are located near the TE Kakanj, the Banovic, Đurđevik and Kreka mines near the TE Tuzla, the Stanari mine near the TE Stanari, the Terex Kop and Ugljevik mines near the TE Ugljevik and the Gacko mine near the TE Gacko.[40]

The main hydropower plants are HE Visegrad, RHE Capljina, HE Grabovica, HE Trebinje, HE Salakovac, HE Rama, HE Jablanica, HE Bocac, HE Mostar, HE Jajce 1 and HE Jajce2. RHE Capljina is the only pumped hydro storage unit.[40],[41],[42]

Major rivers flowing through or passing Bosnia and Herzegovina are rivers Sava, Drina, Neretva, Una, Bosna, Vrbas, Sana and Trebišnjica.[42]

Beside the two main power generation sources with a total thermal power capacity of 2,516 MW and 2,180.24 MW of hydropower generation, Bosnia and Herzegovina has 14 MW of solar capacities and 50,6 MW of wind power with its first wind power plant VE Mesihovina.[40],[46]

Total energy mix of Bosnia and Herzegovina presented in percentage shows that lignite-fired thermal power plants account for 60.46%, hydropower plants for 37.65% and other energy sources for 1.89%.[40]

More on the power plants data in Table 3.5.

**Table 3.5. The list of the major power plants in Bosnia and Herzegovina [40],[41],[42],[45]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| TE Tuzla | 730 | STUR | LIG |
| TE Kakanj | 416 | STUR | LIG |
| TE Ugljevik | 269 | STUR | LIG |
| TE Gacko | 289 | STUR | LIG |
| TE Stanari | 300 | STUR | LIG |
| HE Bocac | 110 | HDAM | WAT |
| HE Jablanica | 181 | HDAM | WAT |
| HE Rama | 161 | HDAM | WAT |
| HE Salakovac | 210 | HDAM | WAT |
| HE Trebinje | 179 | HDAM | WAT |
| HE Visegrad | 315 | HDAM | WAT |
| RHE Capljina | 430 | HPHS | WAT |
| HE Grabovica | 114 | HROR | WAT |
| HE Mostar | 72 | HROR | WAT |
| HE Jajce 1 | 60 | HROR | WAT |
| HE Jajce 2 | 30 | HROR | WAT |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

### 3.1.4. *Montenegro*

The power system of Montenegro consists of one thermal coal-fired thermal power plant, TE Pljevlja, two larger hydropower plants, HE Piva and HE Perucica, with few smaller hydropower plants, HE Bistrica, HE Orah, HE Sekular, HE Pljevlja, HE Glava Zete, HE Slap Zete, HE Muskovica Rijeka, HE Savnik, HE Lijeva Rijeka, HE Podgor and HE Rijeka Crnojevica.[40],[41]

Beside thermal power plant TE Pljevlja (210 MW) and hydropower plants (673 MW), Montenegro has wind power capacity of 72 MW with their first wind power plant Krnovo that started operating in 2017.[40],[47]

Total energy mix of Montenegro presented in percentage shows that hydropower plants account for 69.66%, thermal power plant TE Pljevlja for 22.81% and other energy sources for 7.53%.

More on the power plants data in Table 3.6.

**Table 3.6. The list of the major power plants in Montenegro, [40],[41],[42],[45]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| TE Pljevlja | 210 | STUR | HRD |
| HE Piva | 360 | HDAM | WAT |
| HE Perucica | 310 | HDAM | WAT |
| mHE Bistrica | 5.1 | HROR | WAT |
| mHE Orah | 1.71 | HROR | WAT |
| mHE Sekular | 1.71 | HROR | WAT |
| HE Glava Zete | 5.36 | HROR | WAT |
| HE Slap Zete | 2.4 | HROR | WAT |
| HE Pljevlja | 114 | HROR | WAT |
| HE Muskovica Rijeka | 0.84 | HROR | WAT |
| HE Savnik | 0.2 | HROR | WAT |
| HE Podgor | 0.395 | HROR | WAT |
| HE Rijeka Crnojevica | 0.555 | HROR | WAT |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

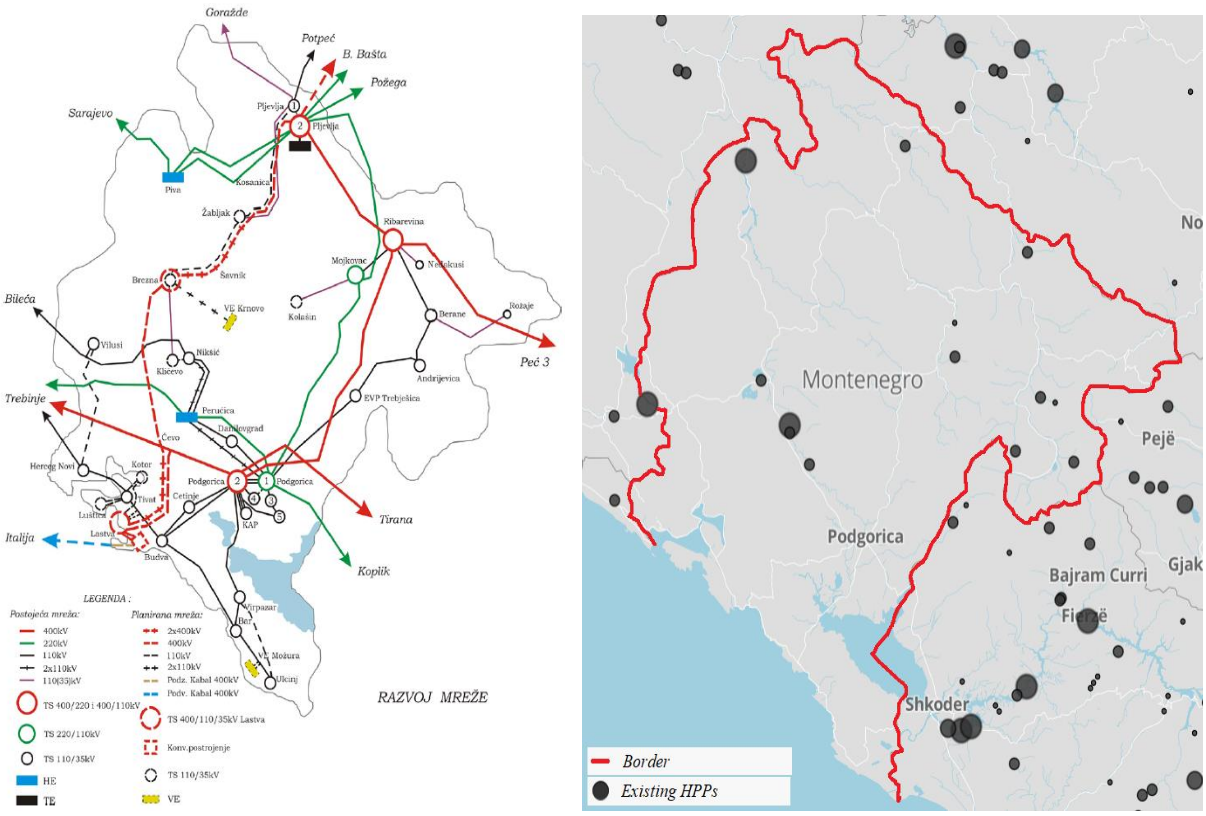



**Figure 3.4. Transmission network of Montenegro with locations of larger power plants (left),[48]; Locations of existing hydropower plants (right),[32]**

### 3.1.5. *North Macedonia*

The power system of North Macedonia consists of three thermal power plants and several hydropower plants. Thermal power plants TE Bitola and TE Oslomej are lignite-fired thermal power plants, which utilize nearby coal mines Suvodol and, Oslomej East and West, respectively. The TE-TO AD Skopje is gas-fired combined cycle cogeneration power plant.[40]

The largest hydropower plants are HE Tikvesh, HE Shpilje, HE Kozjak, HE Globcica, HE Sveta Petka and the Mavrovo Cascade consisted of HE Vrutok, HE Raven and HE Vrben. Besides larger hydropower plants, North Macedonia has a capacity of 97 MW of the small hydropower plants.[40],[41],[42],[45]

The only wind power plant is the Vatren Park Bogdanci with a power output of 35 MW that started operating in 2014.[40]

Based on IEA Statistic, the percentage of electricity generation by fuel for the year 2015 shows the usage of coal, hydropower, gas, wind and other energy sources of 58.26%, 33.03%, 3.24%, 2.14% and 3.33%, respectively.[49]

More on the power plants data in Table 3.7.

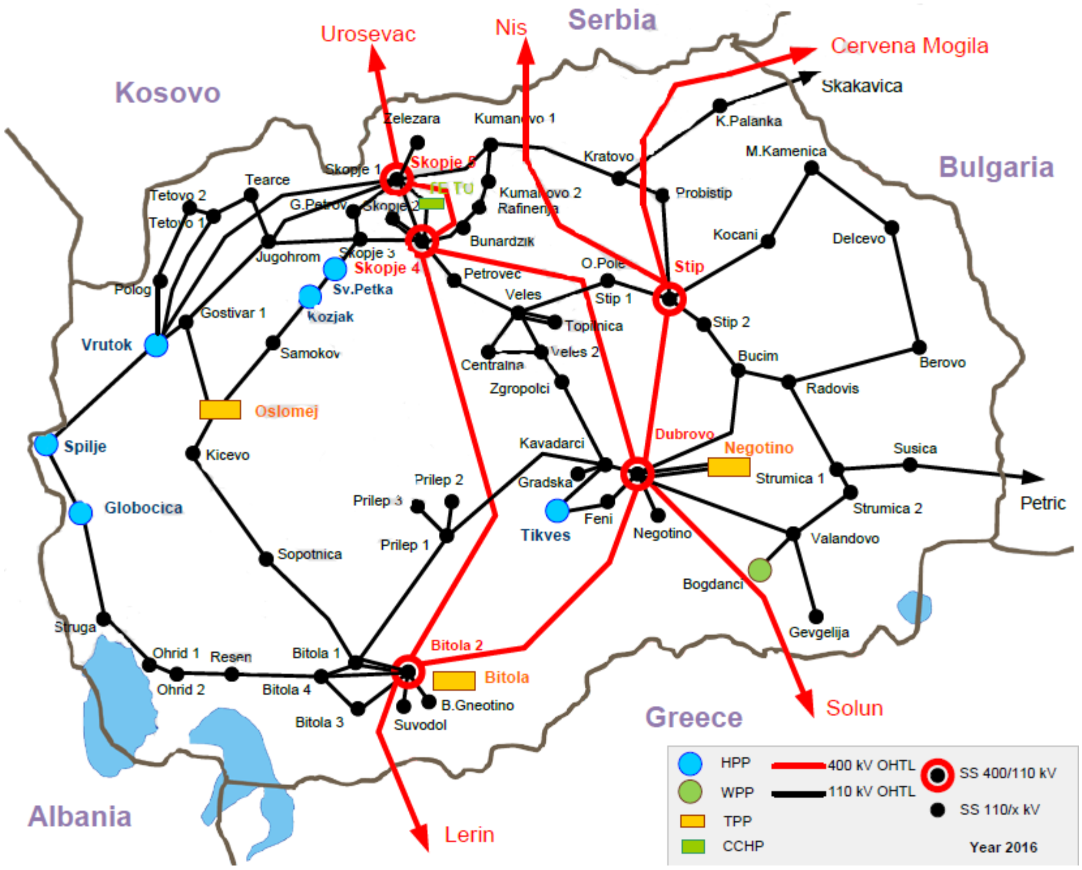



**Figure 3.5. Transmission network of North Macedonia with locations of larger power plants [48]**

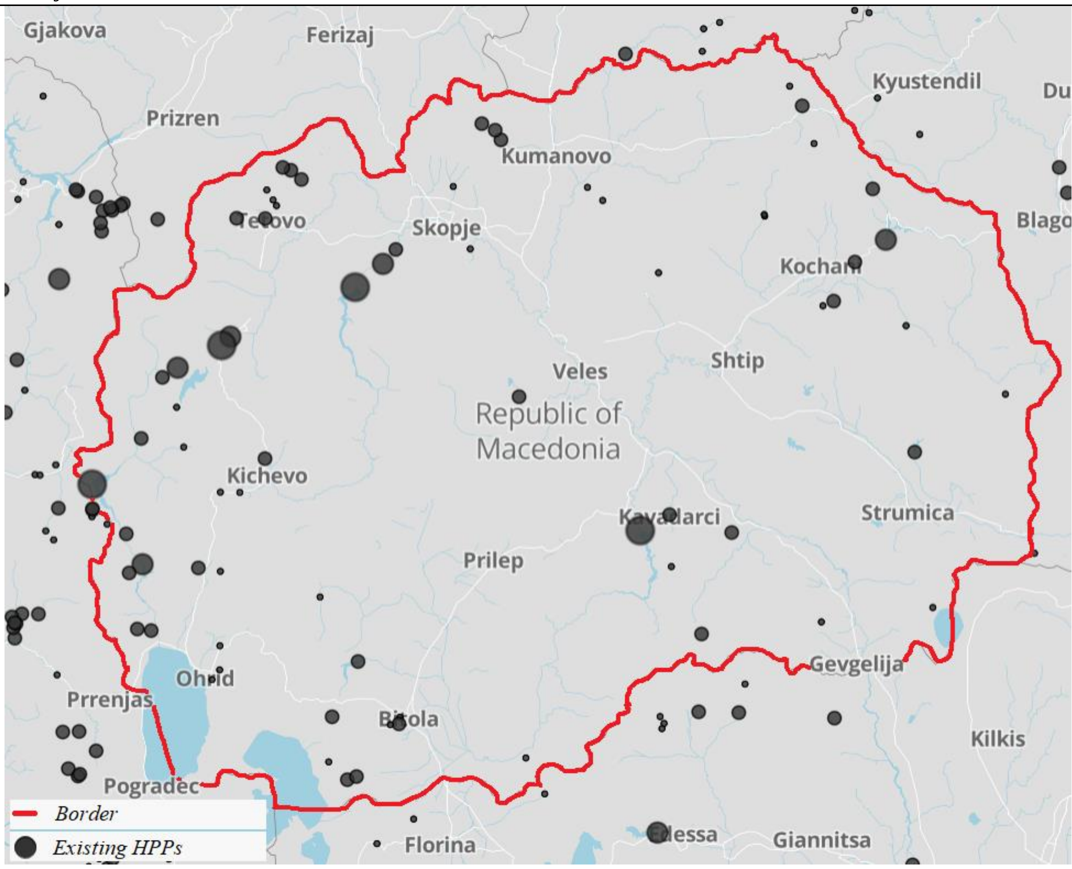



**Figure 3.6. Locations of existing hydropower plants in North Macedonia [32]**

**Table 3.7. The list of the major power plants in North Macedonia, [40],[41],[42],[45]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| TE Bitola | 699 | STUR | LIG |
| TE Oslomej | 125 | STUR | LIG |
| TE-TO AD Skopje | 251 | COMC | GAS |
| Mavrovo Cascade | 207 | HDAM | WAT |
| HE Tikvesh | 114 | HDAM | WAT |
| HE Shpilje | 84 | HDAM | WAT |
| HE Kozjak | 82 | HDAM | WAT |
| HE Globacica | 42 | HDAM | WAT |
| HE Sveta Petka | 36.4 | HDAM | WAT |
| HE Kalimanci | 13.8 | HROR | WAT |
| HE Matka | 8 | HROR | WAT |
| VE Vatren Park Bogdanci | 35 | WTON | WIN |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

### 3.1.6. *Serbia*

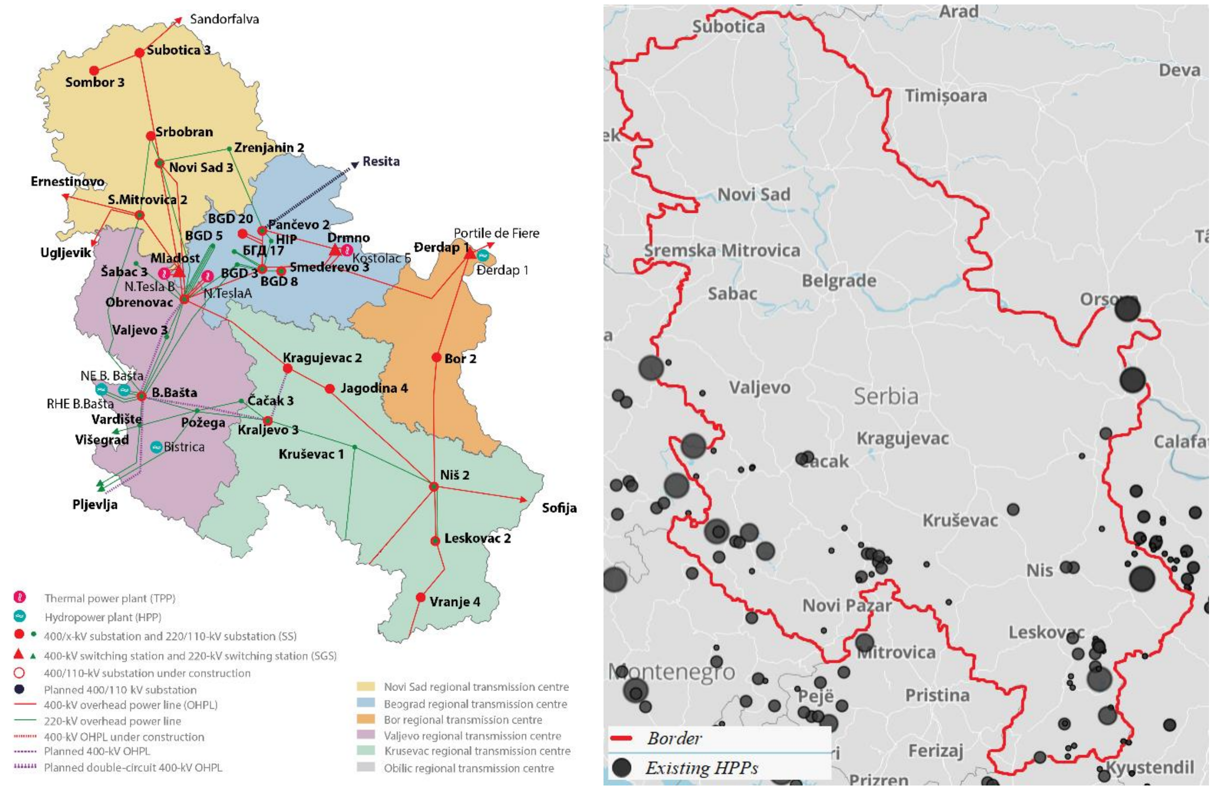



**Figure 3.7. Transmission network of Serbia with locations of larger power plants (left),[52]; Locations of existing hydropower plants (right), [32]**

Serbian power system consists of ten thermal power plants and a number of hydropower plants as they represent a big share of electricity generation units. The lignite-fired thermal power plants are TE Kolubara, TE Kostolac A, TE Kostolac B, TE Morava, TE Nikola Tesla A and TE Nikola Tesla B. The lignite coal is provided from coal mines Kostolac and Kolubara. TETO Novi Sad, TETO Zrinjanin and TETO Sremska Mitrovica are combined heat and power thermal power plants that utilize gas as a power source.[40],[41],[45],[50]

Major hydropower plants are HE Bajina Bašta, HE Djerdap 1, HE Djerdap 2, HE Zvornik. HE Pirot, HE Bistrica, HE Kokin Brod, HE Potpec, HE Uvac, HE Vrla 1-4 and RHE Bajina Bašta. Beside mentioned larger hydropower plants, Serbia has small hydropower capacities with a total 62 MW of power output.[40],[41][42],[45]

With construction completion of Alibunar wind farm in late 2018, the total wind power output of Serbian power sector reached 67 MW. The largest wind farms are VE Alibunar, VE Malibunar, VE Kula and VE Izbiste with a power output of 42 MW, 8 MW, 9.9 MW and 6.6 MW, respectively.[40],[51] Based on IEA Statistic, the percentage of electricity generation by fuel for the year 2015 shows the usage of coal, hydropower and other energy sources (oil, gas, biofuels, waste, solar and wind) of 71.09%, 28.17% and 0.74%, respectively.[49]

More on the power plants data in Table 3.8.

**Table 3.8. The list of the major power plants in Serbia, [40],[41],[42],[50],[51]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| TE Kolubara | 270 | STUR | LIG |
| TE Kostolac A | 310 | STUR | LIG |
| TE Kostolac B | 698 | STUR | LIG |
| TE Morava | 125 | STUR | LIG |
| TE Nikola Tesla A | 1650 | STUR | LIG |
| TE Nikola Tesla B | 1240 | STUR | LIG |
| TETO Novi Sad | 245 | COMC | GAS |
| TETO Zrenjanin | 100 | COMC | GAS |
| TETO Sremska Mitrovica | 45 | COMC | GAS |
| HE Bajina Basta | 420 | HROR | WAT |
| HE Djerdap 1 | 1083 | HROR | WAT |
| HE Djerdap 2 | 270 | HROR | WAT |
| HE Zvornik | 96 | HROR | WAT |
| HE Pirot | 80 | HDAM | WAT |
| HE Bistrica | 102 | HDAM | WAT |
| HE Kokin Brod | 22 | HDAM | WAT |
| HE Potpec | 54 | HDAM | WAT |
| HE Uvac | 36 | HDAM | WAT |
| HE Vrla 1-4 | 128.6 | HDAM | WAT |
| RHE Bajina Basta | 614 | HDAM | WAT |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

### 3.1.7. *Kosovo*

Kosovo power system consists of two thermal power plants and several hydropower plants.

Thermal power plants TE Kosovo A and TE Kosovo B are lignite-fired thermal power plants.

Thermal power plants utilize nearby coal mine named Southwest Sibovc mine.[40]

The largest hydropower plant is HE Ujmani with a net power output of 35 MW. Ten smaller hydropower plants add up to total 40 MW of power output, which together with HE Ujmani, account for 75 MW of total power capacities.[40],[42]

Putting the wind park VE Kitka in operation, total wind power output rose up to the 33.77 MW.[40]

Based on IEA Statistic, the percentage of electricity generation by fuel for the year 2015 shows the usage of coal, hydropower and oil of 97.47%, 2.29% and 0.24%, respectively.[49]

More on the power plants data in Table 3.9.

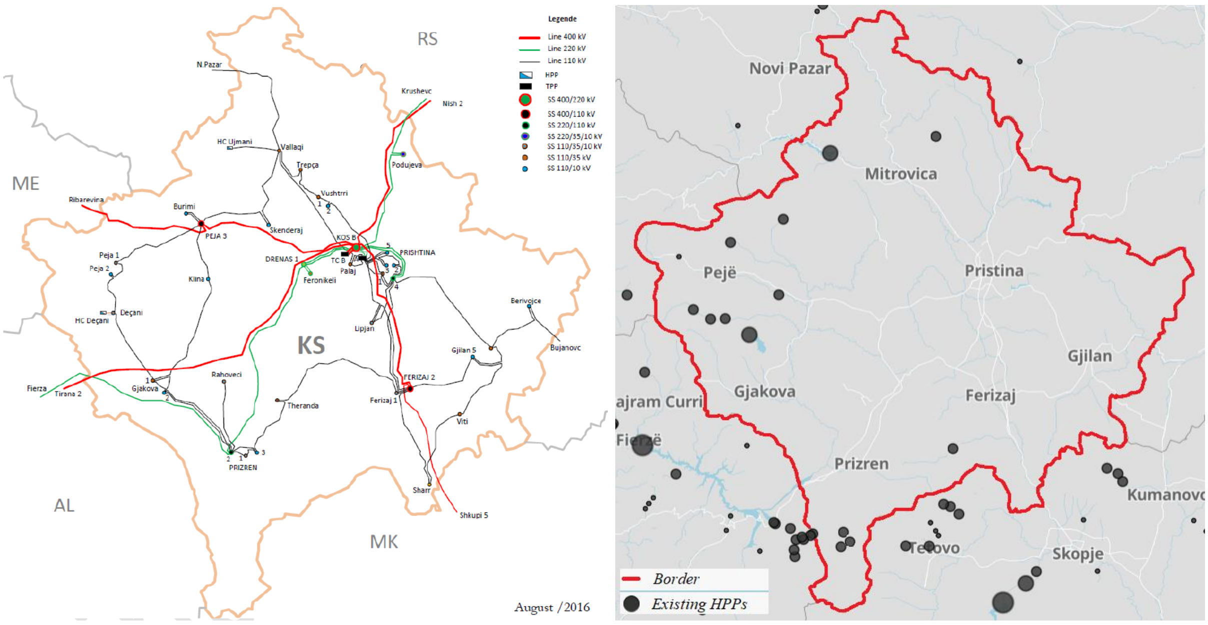



**Figure 3.8. Transmission network of Kosovo with locations of larger power plants (left),[45]; Locations of existing hydropower plants (right), [32]**

**Table 3.9. The list of the major power plants in Kosovo, [40],[41],[42]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| TE Kosovo A | 432 | STUR | LIG |
| TE Kosovo B | 528 | STUR | LIG |
| HE Ujmani | 35 | HDAM | WAT |
| HE Decani | 9.9 | HROR | WAT |
| HE Bellaje | 8 | HROR | WAT |
| Small HPPs | 40 | HROR | WAT |
| Wind Parks | 33.7 | WTON | WIN |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

## 3.2. Slovenia

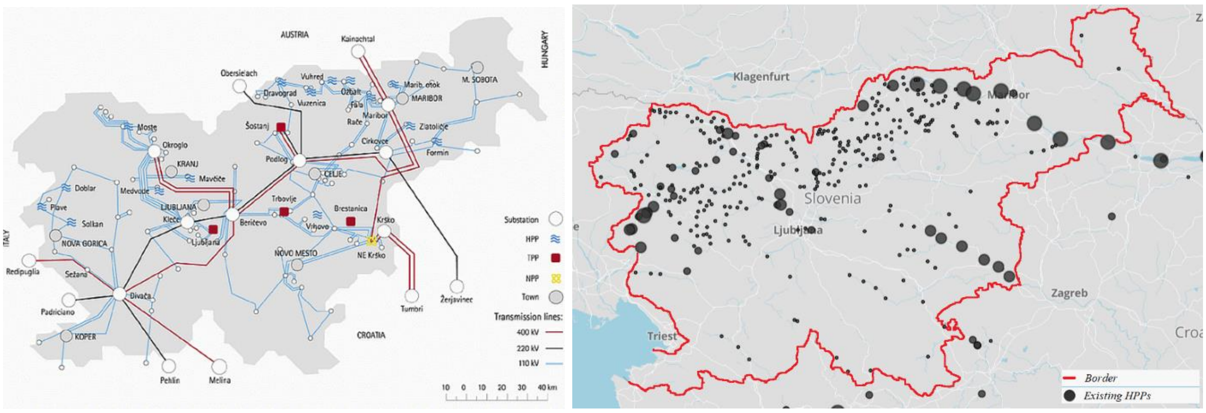



**Figure 3.9. Transmission network of Slovenia with locations of larger power plants (left), [62]; Locations of existing hydropower plants (right), [32]**

Slovenian power system mainly consists of three fossil fuel powered thermal power plants, one nuclear power plant and a number of hydropower plants.

TE Sostanj and TE-TO Ljubljana are lignite-fired thermal power plants with both being CHP power stations. The thermal power plant TPP Brestenica utilize gas as a power source. Nuclear power plant NE Krsko is a shared project between Croatia and Slovenia with power plant's energy output shared equally.[45],[53],[54],[55],[56],[58]

Largest hydropower plants are located on three main rivers in Slovenia, Soča, Sava and Drava Rivers. Hydropower plants can be divided into Soca HPP Chain, Sava HPP Chain and Drava HPP Chain with most of the units being run-of-river type hydropower plants.[59]

The largest hydropower plants on the Drava River are HE Dravograd, HE Vuzenica, HE Vuhred, HE Ozbalt, HE Fala, HE Mariborski Otok, HE Zatolicje and HE Formin. The hydropower plants on the Soča River are HE Doblar I, HE Doblar II, RHE Avche, HE Plave I, HE Plave II and HE Solkan with RHE Avche being the only pumped hydropower plant in Slovenia. Main hydropower plants on the upper part of the Sava River are HE Moste, HE Mavcice and HE Medvode, while the largest hydropower plants on the downstream part of the Sava River are HE Vrhovo, HE Bostanj, HE Blanca, HE Krsko, HE Brezice and HE Mokrice. Beside the mentioned larger hydropower plants, Slovenia has a large number of small hydropower plants.[32],[45],[53],[54],[55],[59],[60]

Beside thermal power and hydropower plants, Slovenia has smaller capacities in energy generation from waste or biomass (57 MW), wind power (3 MW) and solar power generation (275 MW).[61]

Based on IEA Statistic, the percentage of electricity generation by fuel for the year 2015 shows the usage of nuclear energy, coal, hydropower, gas, solar power and other energy sources (wind, biofuels, waste, oil) of 37.4%, 29.04%, 27.09%, 2.68%, 1.81% and 1.98%, respectively.[49]

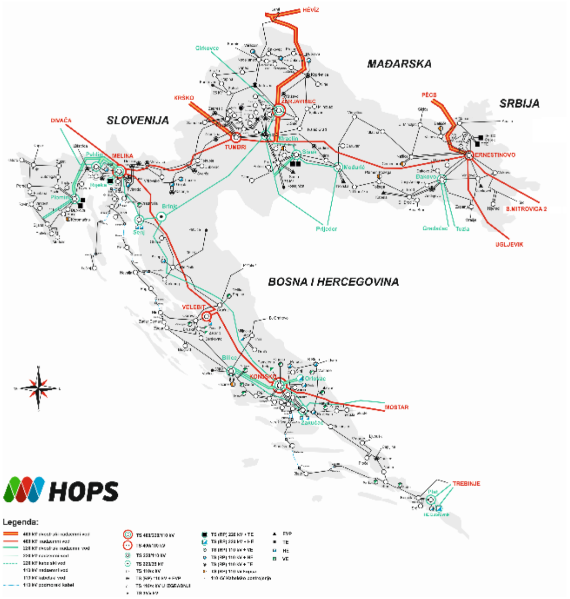
More on the power plants data in Table 3.10.

**Table 3.10. The list of the major power plants in Slovenia,[32],[45],[53]-[60]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| NE Krsko | 696 | STUR | NUC |
| TE Sostanj | 1217 | STUR | LIG |
| TPP Brestanica | 297 | GTUR | GAS |
| TETO Ljubljana | 134 | STUR | HRD |
| HE Dravograd | 21 | HROR | WAT |
| HE Vuzenica | 52 | HROR | WAT |
| HE Vuhred | 61 | HROR | WAT |
| HE Ozbalt | 61 | HROR | WAT |
| HE Fala | 57 | HROR | WAT |
| HE Mariborski Otok | 60 | HROR | WAT |
| HE Zatolicje | 126 | HROR | WAT |
| HE Formin | 127 | HROR | WAT |
| HE Doblar I and II | 70 | HROR | WAT |
| RHE Avche | 185 | HPHS | WAT |
| HE Plave I and II | 42 | HROR | WAT |
| HE Solkan | 31 | HROR | WAT |
| HE Moste | 13 | HROR | WAT |
| HE Mavcice | 38 | HROR | WAT |
| HE Medvode | 19 | HROR | WAT |
| HE Vrhovo | 34 | HROR | WAT |
| HE Bostanj | 32 | HROR | WAT |
| HE Krsko | 38 | HROR | WAT |
| HE Brezice | 45 | HROR | WAT |
| HE Mokrice | 28.05 | HROR | WAT |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

### 3.3. Croatia



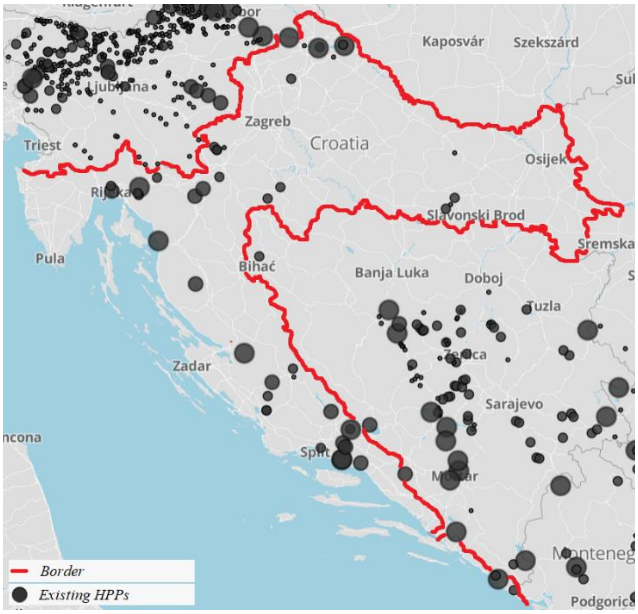




**Figure 3.10. Transmission network of Croatia with locations of larger power plants (left), [68]; Locations of existing hydropower plants (right), [32]**

Croatian powers system is mainly composed of eight larger thermal power plants, a number of hydropower plants and wind power capacity of 582 MW.[55],[61]

Thermal power plants EL-TO Zagreb, TE-TO Osijek, TE-TO Sisak (BLOK C) and TE-TO Zagreb are CHP units that utilize gas as a power source. TE-TO Sisak refers to the set of the three units with one of them (BLOK C) being Combined Cycle Gas Turbine Unit (CCGT) with a power output of 230 MWe and 50 $MW_h$ commissioned in 2015. The other two units of the TE-TO Sisak are steam turbine powered generators that utilize oil as a power source. KTE Jertovec with a power output of 88 MW is also CCGT unit that uses gas as a power source. Beside two units of TE-TO Sisak using oil as a power source, the thermal power plant TE Rijeka uses the same fuel for electricity generation. The only thermal power plant that uses coal as a power source is TE Plomin.[45],[55],[61],[63],[64]

Hydropower plants are divided into Southern HPPs, Western HPPs, Northern HPPs and HES Dubrovnik.[63]

Northern HPPs, HE Varazdin, HE Cakovec and HE Dubrava are located on the Drava River. HES Vinodol is a system that includes hydropower plants CHE Fuzine, RHE Lepenica and HE Vinodol. Together with hydropower plants HES Senj (HE Senj and HE Sklope), HE Rijeka, HE Zeleni Vir, HE Gojak, HE Lešće and HE Gojak, HES Vinodol forms Western HPPs which utilize waters of the Kupa River (HE Ozalj); Ogulinska Dobra and Zagorska Mrežnica Rivers

(HE Gojak); Lokvarka, Križ, Ličanka, Benkovac Rivers and Lokvarsko, Lepenica and Bajer Lakes (HES Vinodol); Riječina River (HE Rijeka), Lika and Gacka Rivers (HES Senj) and Dobra River (HE Lesce).[45],[63],[64],[65]

Hydropower plants RHE Velebit, HE Miljacka, HE Golubic, HE Jaruga, mHE Krcic, HE Orlovac, HE Peruća, HE Dale, Zakucac and HE Kraljevac form a group of Southern HPPs utilizing waters of the Cetina, Zrmanja and Krka River Basins.[45,][63],[64],[66],[67]

HES Dubovnik is composed of smaller HE Zavrelje and shared project between Croatia and Bosnia and Herzegovina, HE Dubrovnik, which uses waters of the Trebišnjica River from the Bileća Lake which is located in Bosnia and Herzegovina.[45],[63],[64]

Based on IEA Statistic, the percentage of electricity generation by fuel for the year 2015 shows the usage of hydropower, coal, gas, wind, biofuels, oil and other energy sources (solar, waste) of 57.49%, 20.26%, 10.5%, 6.98%, 2.33%, 1.93% and 0.51%, respectively.[49]

More on the power plants data in Table 3.11.

**Table 3.11. The list of the major power plants in Croatia, [45],[61],[63]-[67]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| EL-TO Zagreb | 90 | STUR | GAS |
| KTE Jertovec | 88 | COMC | GAS |
| TE Plomin | 325 | STUR | HRD |
| TE Rijeka | 320 | STUR | OIL |
| TE-TO Sisak (BLOK A and B) | 396 | STUR | OIL |
| TE TO Sisak (BLOK C) | 230 | COMC | GAS |
| TE-TO Zagreb | 440 | STUR | GAS |
| HE Kraljevec | 46.4 | HROR | WAT |
| HE Varazdin | 92.46 | HROR | WAT |
| HE Dubrava | 79.78 | HROR | WAT |
| HE Cakovec | 77.44 | HROR | WAT |
| HE Gojak | 55.5 | HROR | WAT |
| HE Lesce | 41.2 | HROR | WAT |
| HE Rijeka | 36.8 | HPHS | WAT |
| HE Miljacka | 24 | HROR | WAT |
| mHE Krcic | 0.375 | HROR | WAT |

| | | | |
|---|---|---|---|
| HE Ozalj | 6 | HROR | WAT |
| HE Jaruga | 7.2 | HROR | WAT |
| HE Zeleni Vir | 1.7 | HROR | WAT |
| HE Zakucac | 486 | HDAM | WAT |
| HE Senj | 216 | HDAM | WAT |
| HE Dubrovnik | 252 | HDAM | WAT |
| HE Vinodol | 90 | HDAM | WAT |
| HE Peruca | 60 | HDAM | WAT |
| HE Sklope | 22.5 | HDAM | WAT |
| HE Dale | 40.8 | HDAM | WAT |
| HE Golubic | 7.5 | HDAM | WAT |
| HE Zavrelje | 2.09 | HDAM | WAT |
| RHE Velebit | 276 | HPHS | WAT |
| RHE Orlovac | 237 | HPHS | WAT |
| RHE Lepenica | 0.8 | HPHS | WAT |
| CHE Fuzine | 4.6 | HPHS | WAT |
| Wind Power | 582 | WTON | WIN |
| Solar Power | 52 | PHOT | SUN |

** related to Dispa-SET Manual list of unit types and supported fuels [75]*

### 3.4. Greece

The Greek power system consists of 37 thermal power plants, number of hydropower plants, the wind power capacity of a 2,355 MW and solar power capacity of a 2,441 MW.[2],[61]

Thermal power plants are lignite or gas fired. Thermal power plants Agios Dimitrios, Amyntaio, Kardia, Megalopoli (III and IV) and Florina are lignite-fired units with a total power output of 3,912 MW. Thermal power plants Lavrio, Megalopoli V, Komotini, Korinthos, Protegia, Aliveri, Elpedison Thisvi, Thessaloniki, Alouminio, Heron CC and Heron (I,II and III) are gas-fired units. All mentioned gas units, excluding Heron I,II and II, are also CCGT units. The total installed power output of the gas-fired thermal power plants is 4,902 MW.[2],[61]

Largest hydropower plants are Asomata, Ilarionas, Kastraki, Kremasta, Ladonas, Pigia Aoos, Plastiras, Platanovrysi, Polyfyto, Pournari I, Pournari I, Stratos, Sfikia, Thesavros, Agras and Edessaios. Most of the mentioned units are conventional dam storage hydropower plants with exception of units Sfikia and Thesavros representing pumped hydropower units, and units Agras and Edessaios representing run-of-river type hydropower plants. Total installed hydropower is 3,401 MW[2],[61],[69]

Based on ENTSO-E Statistic, the percentage of electricity generation by fuel for the year 2018 shows the usage of coal, gas, hydropower, wind and solar of 34.76%, 34.81%, 11.52%, 11.1% and 7.81%, respectively.[61]

More on the power plants data in Table 3.12.

**Table 3.12. The list of the major power plants in Greece, [2],[61],[69]**

| Unit | Power Capacity [MW] | Type* | Fuel* |
|---|---|---|---|
| Lavrio | 928 | COMC | GAS |
| Megalopoli V | 500 | COMC | GAS |
| Komotini | 476 | COMC | GAS |
| Korinthos | 433 | COMC | GAS |
| Protegia CC | 432 | COMC | GAS |
| Aliveri | 417 | COMC | GAS |
| Thisvi Elpedison | 410 | COMC | GAS |
| Thessaloniki | 400 | COMC | GAS |
| Alouminio | 334 | COMC | GAS |
| Heron CC | 422 | COMC | GAS |
| Heron I, II, III | 147 | GTUR | GAS |
| Agios Dimitrios | 1456 | STUR | LIG |
| Florina | 289 | STUR | LIG |
| Kardia | 1103 | STUR | LIG |
| Amyntaio | 546 | STUR | LIG |
| Megalopoli III, IV | 511 | STUR | LIG |
| Asomata | 108 | HDAM | WAT |
| Ilationas | 154 | HDAM | WAT |
| Kastraki | 320 | HDAM | WAT |
| Kremasta | 437 | HDAM | WAT |
| Ladonas | 70 | HDAM | WAT |
| Pigai Aoos | 210 | HDAM | WAT |

| | | | |
|---|---|---|---|
| Plastiras | 130 | HDAM | WAT |
| Platanovrysi | 116 | HDAM | WAT |
| Polyfyto | 375 | HDAM | WAT |
| Pournari 1 | 304 | HDAM | WAT |
| Pournar 2 | 30 | HDAM | WAT |
| Stratos | 150 | HDAM | WAT |
| Sfikia | 315 | HPHS | WAT |
| Thesavros | 384 | HPHS | WAT |
| Agras | 50 | HROR | WAT |
| Edessaios | 19 | HROR | WAT |
| Wind Power | 2,355 | WTON | WIN |
| Solar Power | 2,441 | PHOT | SUN |

* *related to Dispa-SET Manual list of unit types and supported fuels [75]*

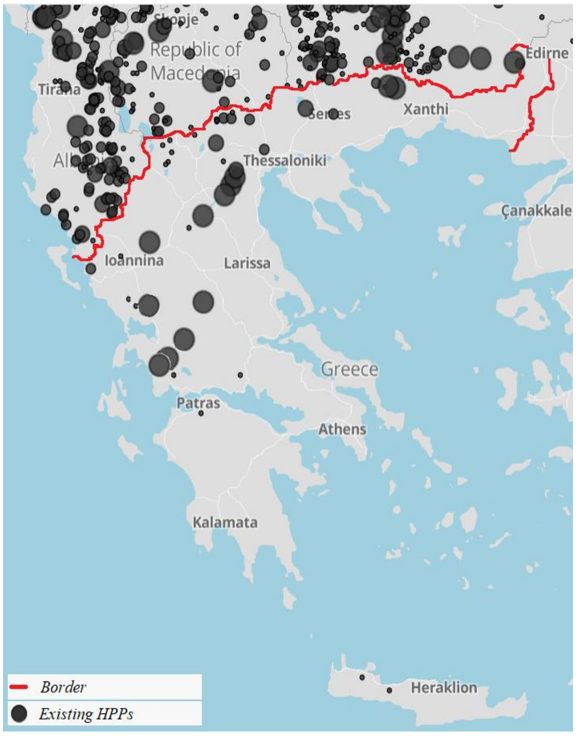




**Figure 3.11. Transmission network of Greece with locations of larger power plants (left), [70]; Locations of existing hydropower plants (right), [32]**

# 4. MODEL DESCRIPTION

The modeling of the region is composed of three steps. The Dispa-SET model is divided into the Dispa-SET Medium-Term Hydrothermal Coordination (Dispa-SET MTHC) and Dispa-SET Unit Commitment and Dispatch (Dispa-SET UCD) model. Both models are linked to the rainfall-runoff hydrological LISFLOOD model. Results from the LISFLOOD model, in form of water inflows, are used as input data for both Dispa-SET models. Steps of the modeling are represented in Figure 4.1.[6]

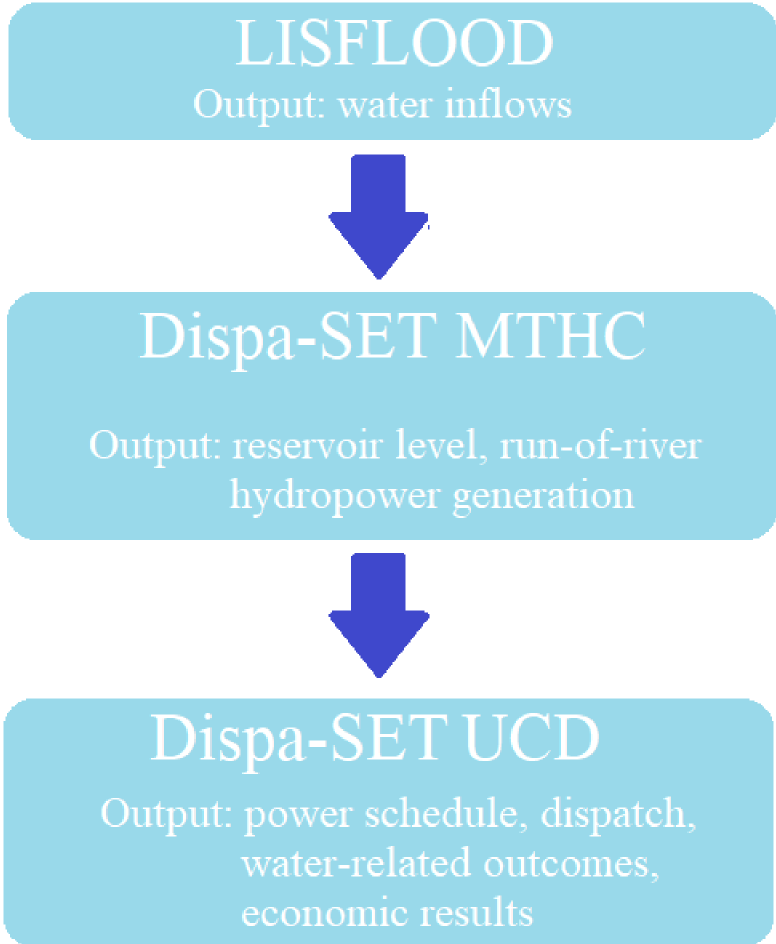



**Figure 4.1. Modeling steps and their outputs [6]**

The first step represents the LISFLOOD model which is solved to give the output of the water inflows for the Dispa-SET model. Water inflows impose constraints on hydropower plants, and for the later work, water constrained limitation for the thermal power plants.[6]

The second step represents the Dispa-SET MTHC model, which runs at daily time steps in order to provide management of water resources. Its output in the form of reservoir levels and the hydropower generation of the run-of-river units is later passed for the Dispa-SET UCD model.[6]

The third step is the Dispa-SET UCD model which runs at hourly time steps and gives output in terms of power dispatch and schedule, water-related results and economic results.[6]

## 4.1. LISFLOOD

As a source of the needed inflows for the Dispa-SET MTHC, and later Dispa SET UCD model, the LISFLOOD model represents the important role for this study. The model will be only briefly discussed since it is not being used in the scope of this study yet the data related to the inflows are provided by JRC.

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, assessing the effects of river regulation measures, effects of land-use change and effects of climate change.[71]

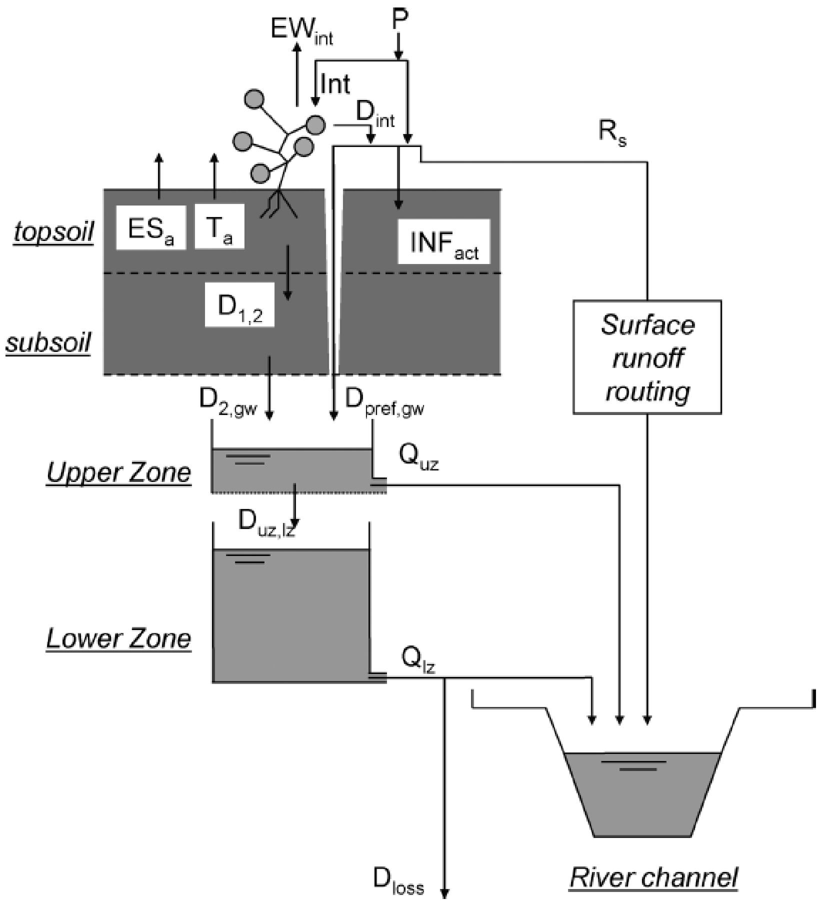



**Figure 4.2. Overview of the LISFLOOD model. P = precipitation; Int = interception; $EW_{int}$ = evaporation of intercepted water; $D_{int}$ = leaf drainage; $ES_a$ = evaporation from soil surface; $T_a$ = transpiration (water uptake by plant roots); $INF_{act}$ = infiltration; $R_s$ = surface runoff; $D_{1,2}$ = drainage from top- to subsoil; $D_{2,gw}$ = drainage from subsoil to upper groundwater zone; $D_{pref,gw}$ = preferential flow to upper groundwater zone; $D_{uz,lz}$ = drainage from upper- to lower groundwater zone; $Q_{uz}$ = outflow from upper groundwater zone; $Q_l$ = outflow from lower groundwater zone; $D_{loss}$ = loss from lower groundwater zone. Note that snowmelt is not included in the Figure (even though it is simulated by the model)., [72]**

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.[71]

There is an overview of the model structure presented in Figure 4.2. 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 surface runoff to the nearest river channel and sub-model for the routing of channel flow. Simulated processes include infiltration, snowmelt, interception of rainfall, leaf drainage, evaporation, water uptake by vegetation, surface runoff, 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 [71].[71],[72]

## 4.2. Dispa-SET Medium-Term Hydrothermal Coordination

The Dispa-SET MTHC is a model 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 mens that thermal power units are aggregated by fuel and country, because the main scope of the MTHC model is to get results on hydropower generation and reservoir levels, and including the each thermal unit itself would substantialy increase the run time of the model. The MTHC problem can be characterized as large-scale, nonlinear and nonconvex optimization.[1]

The problem can be solved from two perspectives. The extensive form also knows as deterministic equivalent, which is used in this study, and the stochastic form.[1]

The deterministic MTHC problem assumes fixed water inflows, and based on the formulation of the hydro and thermal related technical features, the problem can be formulated as linear programming, nonlinear programming or mixed-integer linear programming.[1]

Related to the stochastic form, the model is based on the addition of uncertainty as hydrological scenarios for each planning stage, which consist of the amount of the water available for the electricity generation at each stage through the horizon. Scenarios are built with information from the previous year. There are two ways to tackle the stochastic problem, vertical by stage/time and horizontal by scenarios.[73]

The deterministic form can be used to perform a scenario-based analysis for certain years, while the stochastic form is more valuable when models are used for production because the inherent uncertainty of different variables could affect the real-time operational decisions.[1]

In this study, the deterministic approach is used and it is defined as a constrained linear programming problem in GAMS.[74]

The model sets are represented in Table 4.1., variables in Table 4.2 and model parameters in Table 4.3.

**Table 4.1. Model sets, [6]**

| Sets | |
|---|---|
| p | Time periods |
| ut | Thermal power plants |
| ur | Renewable power plants: 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 (Based on the Dispa-SET manual list of fuels [75]) |

**Table 4.2. Model variables, [6]**

| 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 4.3. Model parameters [6]**

| Name | Unit | Description |
|---|---|---|
| dt | h | Period duration |
| Gravity | $m/s^2$ | Gravity constant |
| Density | $kg/m^3$ | Water density |
| Factor 1 | $Mm^3/(m^3{\cdot}s)$ | Conversion factor from $m^3/s$ to $Mm^3$ |
| Factor 2 | $GWh/((m^3/s){\cdot}m)$ | Conversion factor from $m^3/s$ to GWh |
| Technology (*u*,*t*) | / | Technology [75] |
| 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 function determines the total electricity generation cost during the simulation period. The objective function includes variable costs of electricity generation for all units, the cost of pumping, spillage, energy transmission, curtailment and load shedding.

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

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:

$$\sum_{u \in U(n)} G(p,u) + \sum_{l \in L(n)} FLOW(p,l) = Demand(p,n) + \sum_{u \in PUMP(n)} PUMP(p,u) + CURT(p,n) - LOSTLOAD(p,n) \quad (2)$$

Generation bounds in equation (3) sets the minimum and maximum energy generation of each unit in every time step (day):

$$Pmax \cdot dt > G(p,u) > Pmin(u) \cdot dt \quad (3)$$

The energy generated by hydropower units is set in equation (4). Factor 2 is used to calculate the amount of energy in GWh from initial $m^3/s$.(5)

$$G(p,u) = eta\_turb(u) \cdot DIS(p,u) \cdot NominalHead \cdot Factor2 \quad (4)$$

$$Factor2 = 24(h) \cdot 60(min/h) \cdot 60(s/min) \cdot Gravity \cdot Density \cdot \frac{1}{3600}\left(\frac{Wh}{J}\right) \frac{1}{10^9}\left(\frac{GWh}{Wh}\right) \quad (5)$$

The renewable energy generation from solar and wind power is set in equation (6):

$$G(p,u) = Pmax(u) \cdot Profiles(p,u) \cdot dt \quad (6)$$

The transmission bound is set in equation (7) where it states that power flow cannot be higher than the line capacity:

$$FLOW(p,l) \leq LineCapacity(l) \cdot dt \quad (7)$$

The curtailment bound sets that for each node the curtailment for the units suitable for curtailment (hydropower, wind and solar power) must be lower than the total production (8):

$$CURT(p,n) = \sum_{u \in CURT(n)} G(p,u) \cdot Location(u,n) \quad (8)$$

Water balance bound set that water stored in period *p* plus the outflows is equal to the stored water in period *p-1* plus the inflows (9):

$$RES(p,u) - RES(p-1,u) = Factor1 \cdot (Resources(p,u) - Evaporation(p,u) + UPSTREAM(p,u) + CH(p,u) - DIS(p,u) - SPILL(p,u) - DemandW(p,u)) \quad (9)$$

Minimum water outflow (discharge and spillage) from the hydropower units must be higher than the ecological flow (10):

$$Eco\_flow(p,u) \leq DIS(p,u) + SPILL(p,u) \quad (10)$$

The maximum allowed spillage is used to bound the spillage in equation (11):

$$Spillage\_\mathrm{max}(p,u) \geq SPILL(p,u) \quad (11)$$

The water storage is bounded by the maximum and the minimum storage volumes in the equation (12):

$$Stmax(p,u) \geq RES(p,u) \geq Stmin(p,u) \quad (12)$$

Pumped hydro storage constraints are represented in equations (13) and (14):

$$PUMP(p,u) \leq Pmax(u) \cdot dt \quad (13)$$

$$PUMP(p,u) = CH(p,u) \cdot NominalHead(u) \cdot Factor2 \cdot \frac{1}{eta\_pump} \quad (14)$$

In equation (15) and (16) the reservoirs are assumed to be emptied or filled in 2 months:

$$RES(p,u) - RES(p-1,u) < \frac{Stmax(u)}{60} \quad (15)$$

$$RES(p-1,u) - RES(p-1,u) < \frac{Stmax(u)}{60} \quad (16)$$

To guarantee a minimum use of certain technologies, to match the available statistics, the equations (17) is set:

$$\sum_{u \in U} G(p,u) \cdot Technology(u,t) \geq Duration(n,t) \cdot \frac{1}{365} \sum_{u \in U} Pmax(u) Location(u,n) \quad (17)$$

Set of the equations (1) – (17) is characterized as a linear programming problem.

### 4.3. Dispa-SET Unit Commitment and Dispatch

The Dispa-SET UCD model aims to represent the medium-term operation of large-scale power system. The problem consists of two parts:

- 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,[75],[76]

- Allocation of the total power demand to be achieved among the available generation units so the total power system cost is minimized. This part of the problem is the economic dispatch problem, which determines the output of all generation units.[75],[76]

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.[76]

Continues variables include dispatched power, the curtailed power generation and the shed load in every time step and the binary variables represent the commitment status of all units.[76]

The model features include: minimum and maximum power outputs for the all units, ramping limits, reserves up and down, minimum up and down times, load shedding, curtailment, pumped-hydro storage, non-dispatchable units, constraints on the targets for the renewables and/or $CO_2$ emissions, outages of all units, 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.[76]

The model uses three data types: Set, Parameters and Optimisation Variables. Sets are building a blocks of the model and are listed in Table 4.4. Parameters are coefficients that correspond to the exogenous data provided to the model. The list of the model's parameters is shown in Table 4.5. The model variables are set by the model to minimize the objective function and are listed in Table 4.6.

**Table 4.4. Model sets [77]**

| Sets | |
|---|---|
| f | Fuel types |
| h | Hours |
| i | Time step in the current optimization horizon |
| l | Transmission lines between nodes |
| mk | {DA: Day-Ahead, 2U: Reserve up, 2D: Reserve down} |
| n | Zones within each country (currently one node per country) |
| p | Pollutants |
| t | Power generation technologies |
| tr | Renewable power generation technologies |
| u | Units |
| s(*u*) | Storage units (including hydro reservoirs) |
| chp(*u*) | CHP units |

**Table 4.5. Model parameters [77]**

| Name | Unit | Description |
|---|---|---|
| AvailabilityFactor(u,i) | % | Percentage of nominal capacity available |
| CHPPowerLossFactor(u) | % | Power loss when generating heat |
| CHPPoweToHeat(u) | % | Nominal power-to-heat ratio |
| CHPMaxHeat(chp) | MW | Maximum heat capacity of CHP plant |
| CHPType | / | CHP Type |
| CommittedInitial(u) | / | Initial commitment status |
| CostFixed(u) | €/h | Fixed cost |
| CostLoadShedding(n,h) | €/MWh | Shedding cost |
| CostRampDown(u) | €/MW | Ramp-down cost |
| CostRampUp(u) | €/MW | Ramp-up cost |
| CostShutDown(u) | €/u | Shut-down costs for one unit |
| CostStartUp(u) | €/u | Start-up cost for one unit |
| CostVariableH(u,i) | €/MWh | Variable cost |
| CostHeatSlach(chp,h) | €/MWh | Cost of supplying heat via other means |
| Curtailment(n) | / | Curtailment |
| Demand(mk,n,i) | MW | Hourly demand in each zone |
| Efficiency(u) | % | Power plant efficiency |
| EmissionMaximum(n,p) | €/tP | Emission limit per zone for pollutant p |
| EmissionRate(n,p) | tP/MW | Emission rate of pollutant p from unit u |
| Fuel(u,f) | / | Fuel type used by unit u |
| HeatDemand(chp,h) | MWh/u | Heat demand profile for CHP units |
| K_QuickStart(n) | / | Reserve that can be provided by offline units |
| LineNode(l,n) | / | Line-zone incidence matrix |
| LoadShedding(n,h) | MW | Load that may be shed per zone in 1 hour |
| Location(u,n) | / | Location |
| Nunits(u) | / | Number of units inside the cluster |
| OutageFactor(u,h) | % | Outage factor per hour |
| PartLoadMin(u) | % | Percentage of minimum nominal capacity |
| PowerCapacity(u) | MW/u | Installed capacity |
| PowerInitial(u) | MW/u | Power output before initial period |
| PowerMinStable(u) | MW/u | Minimum power for stable generation |
| PowerMustRun(u) | MW | Minimum power output |
| PriceTransmission(l,h) | €/MWh | Price of transmission between zones |
| QuickStartPower(u,h) | MW/h/u | Available max capacity for tertiary reserve |
| RampDownMaximum(u) | MW/h/u | Ramp down limit |
| RampShutDownMaximum(u) | MW/h/u | Shut-down ramp limit |
| RampStartUpMaximum(u) | MW/h/u | Start-up ramp limit |
| RampUpMaximum(u) | MW/h/u | Ramp up limit |
| Reserve(t) | / | Reserve provider |
| StorageCapacity(s) | MWh/u | Storage capacity |
| StorageChargingCapacity(s) | MW/u | Maximum charging capacity |
| StorageChargingEfficiency(s) | % | Charging efficiency |
| StorageDischargeEfficiency(s) | % | Discharge efficiency |
| StorageInflow(s,h) | MWh/u | Storage inflows |

| | | |
|---|---|---|
| StorageInitial(s) | MWh | Storage level before initial period |
| StorageMinimum(s) | MWh/u | Minimum storage level |
| StorageOutflow(s,h) | MWh/u | Storage outflows |
| StorageProfile(u,h) | MWh | Storage long-term profile |
| Technology(u,t) | / | Technology type |
| TimeDownMinimum(u) | h | Minimum down time |
| TimeUpMinimum(u) | H | Minimum up time |
| VOLL() | €/MWh | Value of lost load |

**Table 4.6. Model variables [77]**

| Name | Unit | Description |
|---|---|---|
| Committed(u,h) | / | Unit committed at hour h |
| CostStartUpH(u,h) | € | Cost of start up |
| CostShutDownH(u,h) | € | Cost of shutting down |
| CostRampUpH(u,h) | € | Ramping cost |
| CostRampDownH(u,h) | € | Ramping cost |
| CurtailedPower(n,h) | MW | Curtailed power at node n |
| Flow(l,h) | MW | Flow through lines |
| Heat(chp,h) | MW | Heat output by CHP plant |
| HeatSlack(chp,h) | MW | Heat satisfied by other sources |
| Power(u,h) | MW | Power output |
| PowerMaximum(u,h) | MW | Power output |
| PowerMinimum(u,h) | MW | Power output |
| Reserve_2U(u,h) | MW | Spinning reserve up |
| Reserve_2D(u,h) | MW | Spinning reserve down |
| Reserve_3U(u,h) | MW | Nonspinning quick start reserve up |
| ShedLoad(n,h) | MW | Shed load |
| StorageInputs(s,h) | MWh | Charging input for storage units |
| StorageLevel(s,h) | MWh | Storage level of charge |
| Spillage(s,h) | MWh | Spillage from water reservoirs |
| SystemCost(h) | € | Total system cost |
| LL_MaxPower(n,h) | MW | Deficit in term of maximum power |
| LL_RampUp(u,h) | MW | Deficit in term of ramping up for each plant |
| LL_RampDown(u,h) | MW | Deficit in term of ramping down |
| LL_MinPower(n,h) | MW | Power exceeding the demand |
| LL_2U(n,h) | MW | Deficit in reserve up |
| LL_3U(n,h) | MW | Deficit in reserve up – non spinning |
| LL_2D(n,h) | MW | Deficit in reserve down |

The goal of the unit commitment model is minimizing the equation (18), which describes the total power system cost. The equation (18) represents the objective function composed of sums of the different cost that are part of the power system, such as start-up and shut down costs, fixed, variable, ramping, transmission-related, load shedding and lost load costs.[77]

$$
\begin{aligned}
SystemCost = \sum_{u,n,i} \big[ & CostStartUp_{u,i} + CostShutDown_{u,i} + CostFired_u \cdot Committed_{u,i} \\
& + CostVariable_{u,i} \cdot Power_{u,i} + CostRampUp_{u,i} + CostRampDown_{u,i} \\
& + PriceTransmission_{i,l} \cdot Flow_{i,l} + CostLoadShedding_{i,n} \cdot ShedLoad_{i,n} \\
& + CostHearSlack_{chp(u),i} \cdot HeatSlack_{chp(u),i} \\
& + CostVariable_{chp(u),i} \cdot CHPPowerLossFactor_{chp(u)} \cdot Heat_{chp(u),i} \\
& + VOLL_{Power} \cdot \left(LostLoadMaxPower_{i,n} + LostLoadMinPower_{i,n}\right) \\
& + VOLL_{Reserve} \cdot \left(LostLoadReserve2U_{i,n} + LostLoadReserve2d_{i,n}\right) \\
& + VOLL_{Ramp} \cdot \left(LostLoadRampUp_{u,i} + LostLoadRampDown_{u,i}\right)\big]
\end{aligned} \tag{18}
$$

The main constraint is the supply-demand balance in the day-ahead market. In the equation (19), the sum of all power produced by the units in node *n*, the power imported from neighboring 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.[77]

$$
\begin{aligned}
& \sum_{p,u} Power_{u,i} \cdot Location_{u,n} + \sum_{p,u} Flow_{l,i} \cdot LineNode_{l,n} \\
& \qquad = Demand_{DA,n,h} + \sum_{p,u} StorageInput_{s,h} \cdot Location_{s,n} - ShedLoad_{n,i} \\
& \qquad - LL_{MaxPower,n,i} + LL_{MinPower,n,i}
\end{aligned} \tag{19}
$$

Other constraints related to the reserves, power output, ramping, minimum up and down times, storage, heat production, heat storage, emissions, network, curtailment and load shedding can be seen in [75],[76], and [77].

# 5. INPUT DATA

## 5.1. Dispa-SET Medium-Term Hydrothermal Coordination Input Data

### 5.1.1. *Power plants*

As stated before, the study includes countries of the West Balkan region with additional neighboring countries Croatia, Slovenia and Greece. Year 2015 is selected as the reference year, therefore the data used for modeling the power system is related to the reference year.

The list of power plants was collected from multiple sources. Most of the data on existing power plants came from the databases [45],[55] and [61], with the additional information from the national TSO's and energy-related documentation available online. References were mentioned in Section 3. for each country included in this study.

The thermal, wind and solar power plants for the Dispa-SET MTHC were clustered based on the fuel chart described in the Dispa-SET Manual [76] and corresponding country. The naming scheme for the thermal power plants was:

- Country_FUEL_Cluster,

where the *Country* represents the ISO 3166-1 standard to define the country name at the NUTS-1 level, and the *FUEL* refers to the mention fuel chart in [76]. List of the country codes is shown in Table 5.1., while the fuel categorization can be seen in Table 5.2.

**Table 5.1. NUTS-1 zones defined in Dispa-SET for the included region, [76]**

| Code | Country |
|---|---|
| AL | Albania |
| BA | Bosnia and Herzegovina |
| EL | Greece |
| HR | Croatia |
| ME | Montenegro |
| MK | North Macedonia |
| RS | Serbia |
| SI | Slovenia |
| XK | Kosovo |

The clustering method was not used on the hydropower plants because the primary goal of the MTHC model is to get results on the reservoir levels of the storage hydropower plants and hydropower production of the run-of-river hydropower plants. The naming scheme for the hydropower plants was:

- Country_PowerPlantName_Technology,

where *PowerPlantName* refers to the actual power plant name, while *Technology* refers to the defined supported ways of producing electrical energy in the Dispa-SET Manual.[76] List of the supported technologies is represented in Table 5.3. The list of the clustered thermal, wind and solar power plants is shown in Table 5.4., while hydropower plants are listed in Table 5.5. The reference column refers to additional data, not related to databases [45],[55] and [61].

**Table 5.2. Dispa-SET fuel list, [76]**

| Fuel | Examples |
|---|---|
| BIO | Bagasse, Biodiesel, Gas From Biomass, Gasification, Biomass, Briquettes, Cattle Residues, Rice Hulls Or Padi Husk, Straw, Wood Gas (From Wood Gasification), Wood Waste Liquids Excl Blk Liq (Incl Red Liquor, Sludge, Wood,Spent Sulfite Liquor And Oth Liquids, Wood And Wood Waste |
| GAS | Blast Furnace Gas, Boiler Natural Gas, Butane, Coal Bed Methane, Coke Oven Gas, Flare Gas, Gas (Generic), Methane, Mine Gas, Natural Gas, Propane, Refinery Gas, Sour Gas, Synthetic Natural Gas, Top Gas, Voc Gas & Vapor, Waste Gas, WellheadGas |
| GEO | Geothermal steam |
| HRD | Anthracite, Other Anthracite, Bituminous Coal, Coker By-Product, Coal Gas (From Coal Gasification), Coke, Coal (Generic), Coal-Oil Mixture, Other Coal, Coal And Pet Coke Mi, Coal Tar Oil, Anthracite Coal Waste, Coal-Water Mixture, Gob, Hard Coal / Anthracite, Imported Coal, Other Solids, Soft Coal, Anthracite Silt, Steam Coal, Subbituminous, Pelletized Synthetic Fuel From Coal, Bituminous Coal Waste) |
| HYD | Hydrogen |
| LIG | Lignite black, Lignite brown, Lignite |
| NUC | U, Pu |
| OIL | Crude Oil, Distillate Oil, Diesel Fuel, No. 1 Fuel Oil, No. 2 Fuel Oil, No. 3 Fuel Oil, No. 4 Fuel Oil, No. 5 Fuel Oil, No. 6 Fuel Oil, Furnace Fuel, Gas Oil, Gasoline, Heavy Oil Mixture, Jet Fuel, Kerosene, Light Fuel Oil, Liquefied Propane Gas, Methanol, Naphtha, ,Gas From Fuel Oil Gasification, Fuel Oil, Other Liquid, Orimulsion, Petroleum Coke, Petroleum Coke Synthetic Gas, Black Liquor, Residual Oils, Re-Refined Motor Oil, Oil Shale, Tar, Topped Crude Oil, Waste Oil |
| PEA | Peat Moss |
| SUN | Solar energy |
| WAT | Hydro energy |
| WIN | Wind energy |
| WST | Digester Gas (Sewage Sludge Gas), Gas From Refuse Gasification, Hazardous Waste, Industrial Waste, Landfill Gas, Poultry Litter, Manure, Medical Waste, Refused Derived Fuel, Refuse, Waste Paper And Waste Plastic, Refinery Waste, Tires, Agricultural Waste, Waste Coal, Waste Water Sludge, Waste |

The variable generation cost of available technologies is collected from multiple sources. In [78] the comparison of the conventional and non-conventional electricity production is studied, with a list of costs for electricity production from wind, solar, biomass, geothermal, hydropower, nuclear power plants, gas and coal-fired thermal power plants. In [79] detailed analysis on the estimation of costs and technical specifications for the different generation technologies is studied. The cost data is broken into detailed expenditure for the lifetime of the power plants. In [80] the social cost of electricity is studied with the categorization of relevant types of costs differentiating between plant-level, system and external costs. In [81] the key factors affecting the economics of the electricity generation is studied with projected costs for electricity production from different energy sources.

**Table 5.3. Dispa-SET technologies, [76]**

| Technology | Description | Storage |
|---|---|---|
| COMC | Combined cycle | N |
| GTUR | Gas turbine | N |
| HDAM | Conventional hydro dam | Y |
| HROR | Hydro run-of-river | N |
| HPHS | Pumped hydro storage | Y |
| ICEN | Internal combustion engine | N |
| PHOT | Solar photovoltaic | N |
| STUR | Steam turbine | N |
| WTOF | Offshore wind turbine | N |
| WTON | Onshore wind turbine | N |
| CAES | Compressed air energy storage | Y |
| BATS | Stationary batteries | Y |
| BEVS | Battery-powered electric vehicles | Y |
| THMS | Thermal storage | Y |
| P2GS | Power-to-gas storage | Y |

**Table 5.4. List of clustered thermal, solar and wind power plants for the reference year, [45],[55],[61]**

| Cluster | Nominal power [MW] | Cluster | Nominal power [MW] |
|---|---|---|---|
| AL_OIL_Cluster | 98 | HR_SUN_Cluster | 44 |
| BA_LIG_Cluster | 1,704 | MK_LIG_Cluster | 824 |
| BA_OIL_Cluster | 98 | MK_GAS_Cluster | 251 |
| ME_LIG_Cluster | 210 | MK_WIN_Cluster | 35 |
| EL_GAS_Cluster | 4,913 | SI_GAS_Cluster | 297 |
| EL_LIG_Cluster | 4,459 | SI_LIG_Cluster | 1,217 |
| EL_OIL_Cluster | 743 | SI_NUC_Cluster | 696 |
| EL_WIN_Cluster | 1,613 | SI_WST_Cluster | 35 |
| EL_SUN_Cluster | 2,429 | SI_BIO_Cluster | 16 |
| HR_GAS_Cluster | 938 | SI_WIN_Cluster | 3 |
| HR_OIL_Cluster | 716 | SI_SUN_Cluster | 262 |
| HR_HRD_Cluster | 325 | RS_LIG_Cluster | 4,293 |
| HR_WST_Cluster | 6 | RS_GAS_Cluster | 390 |
| HR_BIO_Cluster | 25 | XK_LIG_Cluster | 960 |
| HR_WIN_Cluster | 429 | | |

**Table 5.5. List of hydropower plants for the reference year, [45],[55],[61]**

| Unit | Nominal power [MW] | Installed flow [$m^3$/s] | Nominal head [m] | Water storage [$Mm^3$] | Ref |
|---|---|---|---|---|---|
| AL_Koman_HDAM | 600 | 736 | 96 | 118 | [41] |
| AL_Fierza_HDAM | 500 | 467 | 118 | 2,300 | [41] |
| AL_Banje_HDAM | 73 | 50 | 301 | 272 | [10] |
| AL_Vau Dejes_HDAM | 250 | 565 | 52 | 263 | [41] |
| BA_Bocac_HDAM | 110 | 240 | 66 | 42.9 | [41] |
| BA_Jablanica_HDAM | 181 | 209 | 94 | 288 | [41] |
| BA_Rama_HDAM | 161 | 64 | 285 | 466 | [41] |
| BA_Salakovac_HDAM | 210 | 540 | 42 | 68 | [41] |
| BA_Trebinje_HDAM | 179 | 210 | 22 | 1,082 | [41] |
| BA_Visegrad_HDAM | 315 | 800 | 43 | 161 | [41] |
| BA_Capljina_HPHS | 430 | 225 | 228 | 6.5 | [41] |
| EL_Assomata_HDAM | 108 | 303 | 52 | 10 | [2],[69] |
| EL_Ilarionas_HDAM | 154 | 160 | 130 | 270 | [2],[69] |
| EL_Kastraki_HDAM | 320 | 499 | 96 | 98 | [2],[69] |
| EL_Kremasta_HDAM | 437 | 392 | 165 | 3,300 | [2],[69] |
| EL_Ladonas_HDAM | 70 | 34 | 56 | 46 | [2],[69] |
| EL_Pigai Aoos_HDAM | 210 | 36 | 78 | 144 | [2],[69] |
| EL_Plastiras_HDAM | 130 | 27 | 83 | 300 | [2],[69] |
| EL_Platanovrysi_HDAM | 116 | 181 | 95 | 57 | [2],[69] |
| EL_Polyfyto_HDAM | 375 | 311 | 112 | 1,220 | [2],[69] |
| EL_Pournari 1_HDAM | 304 | 453 | 87 | 303 | [2],[69] |
| EL_Pournari 2_HDAM | 30 | 294 | 15 | 4 | [2],[69] |
| EL_Stratos_HDAM | 150 | 468 | 26 | 11 | [2],[69] |
| EL_Sfikia_HPHS | 315 | 635 | 82 | 18 | [2],[69] |
| EL_Thisavros_HPHS | 384 | 288 | 172 | 565 | [2],[69] |
| HR_Zakucac_HDAM | 486 | 220 | 250.4 | 6,8 | [63] |
| HR_Senj_HDAM | 216 | 60 | 410 | 73.14 | [63] |
| HR_Dubrovnik_HDAM | 234 | 90 | 272 | 555 | [63] |
| HR_Vinodol_HDAM | 90 | 16.7 | 648 | 41.56 | [63] |
| HR_Peruca_HDAM | 60 | 120 | 47 | 565 | [63] |
| HR_Sklope_HDAM | 22.5 | 45 | 60 | 54.86 | [63] |
| HR_Dale_HDAM | 40.8 | 220 | 21 | 3.7 | [63] |
| HR_Golubic_HDAM | 7.5 | 14 | 59 | $5^*$ | [63] |
| HR_Zavrelje_HDAM | 2.09 | 3 | 76 | $5^*$ | [63] |
| HR_Velebit_HPHS | 276 | 100 | 538 | 16.35 | [63] |
| HR_Orlovac_HPHS | 237 | 70 | 380 | 800 | [63] |
| HR_Lepenica_HPHS | 0.8 | 6.2 | 12.22 | 4.469 | [63] |

| | | | | | |
|---|---|---|---|---|---|
| HR_CHE Fuzine_HPHS | 4.6 | 9.9 | 49 | 34.5 | [63] |
| ME_Piva_HDAM | 360 | 240 | 220 | 880 | [41] |
| ME_Perucica_HDAM | 310 | 68 | 549 | 225 | [41] |
| MK_Vrutok+Raven_HDAM | 207 | 57 | 525 | 227 | [41] |
| MK_Tikvesh_HDAM | 114 | 144 | 91.3 | 309.6 | [41] |
| MK_Shpilje_HDAM | 84 | 108 | 85.2 | 506 | [41] |
| MK_Kozjak_HDAM | 82 | 100 | 95 | 550 | [41] |
| MK_Globacica_HDAM | 42 | 50 | 95.29 | 55.3 | [41] |
| MK_Sveta Petka_HDAM | 36.4 | 100 | 40 | 11.4 | [82] |
| RS_Pirot_HDAM | 80 | 45 | 243 | 180 | [41] |
| RS_Bistrica_HDAM | 102 | 36 | 378 | 7.6 | [41] |
| RS_Kokin Brod_HDAM | 22 | 37.4 | 72 | 210 | [41] |
| RS_Potpec_HDAM | 54 | 165 | 38.4 | 25 | [41] |
| RS_Uvac_HDAM | 36 | 43 | 100 | 213 | [41] |
| RS_Vrla 1-4_HDAM | 129 | 18.32 | 338 | 165 | [41] |
| RS_Bajina Basta_HPHS | 614 | 129.2 | 555 | 170 | [41] |
| SI_Avche_HPHS | 185 | 40 | 520 | 2 | [83] |
| XK_Ujmani_HPHS | 35 | 35.68 | 100 | 350 | [41] |
| BA_Grabovica_HROR | 114 | 380 | 34 | | [41] |
| EL_Agras_HROR | 50 | 37 | 156 | | [2],[69] |
| EL_Edessaios_HROR | 19 | 19 | 125 | | [2],[69] |
| HR_Kraljevac_HROR | 46.4 | 55 | 108 | | [63] |
| HR_Varazdin_HROR | 92.46 | 500 | 21.9 | | [63] |
| HR_Dubrava_HROR | 79.78 | 500 | 17.5 | | [63] |
| HR_Cakovec_HROR | 77.44 | 500 | 17.5 | | [63] |
| HR_Gojak_HROR | 55.5 | 57 | 118 | | [63] |
| HR_Lesce_HROR | 41.2 | 122.7 | 38.18 | | [63] |
| HR_Rijeka_HROR | 36.8 | 21 | 212.7 | | [63] |
| HR_Miljacka_HROR | 24 | 30 | 102 | | [63] |
| HR_Krcic_HROR | 0.375 | / | / | | [63] |
| HR_Ozalj_HROR | 6 | 85 | 9.2 | | [63] |
| HR_Jaruga_HROR | 7.2 | 31 | 24.4 | | [63] |
| HR_Zeleni Vir_HROR | 1.7 | 4.4 | 50 | | [63] |
| RS_Bajina Basta_HROR | 420 | 692 | 66 | | [41] |
| RS_Djerdap 1_HROR | 1083 | 4,800 | 27.16 | | [41] |
| RS_Djerdap 2_HROR | 270 | 4,200 | 9 | | [41] |
| RS_Zvornik_HROR | 96 | 620 | 21.6 | | [41] |
| SI_Formin_HROR | 127 | 500 | 29 | | [84] |
| SI_Zatolicje_HROR | 126 | 530 | 33 | | [85] |
| SI_Blanca_HROR | 38 | 500 | 9.29 | | [86] |
| SI_Bostanj_HROR | 32 | 500 | 7.47 | | [86] |

| | | | | | |
|---|---|---|---|---|---|
| SI_Doblar_HROR | 70 | 75 | 45.5 | | [87] |
| SI_Dravograd_HROR | 21 | 420 | 8.9 | | [87] |
| SI_Fala_HROR | 57 | 550 | 14.6 | | [88] |
| SI_Krsko_HROR | 38 | 500 | 9.14 | | [86] |
| SI_Mariborski Otok_HROR | 60 | 550 | 14.2 | | [90] |
| SI_Mavcice_HROR | 38 | 54.5 | 19.5 | | [91] |
| SI_Medvode_HROR | 19 | 150 | 19.1 | | [92] |
| SI_Moste_HROR | 13 | 23 | 65 | | [93] |
| SI_Ozbalt_HROR | 61 | 550 | 17.42 | | [94] |
| SI_Plave_HROR | 42 | 75 | 29 | | [87] |
| SI_Solkan_HROR | 31 | 180 | 20.55 | | [87] |
| SI_Vrhovo_HROR | 34 | 230 | 10.5 | | [95] |
| SI_Vuhred_HROR | 61 | 550 | 17.41 | | [96] |
| SI_Vuzenica_HROR | 52 | 530 | 13.8 | | [97] |

** assumption due to the lack of data online*

### 5.1.2. *Demand profiles*

Demand profiles for all countries have been obtained from the ENTSO-E Power Statistic Platform, with the exception of demand profile for the Kosovo, which was obtained from the database [55].

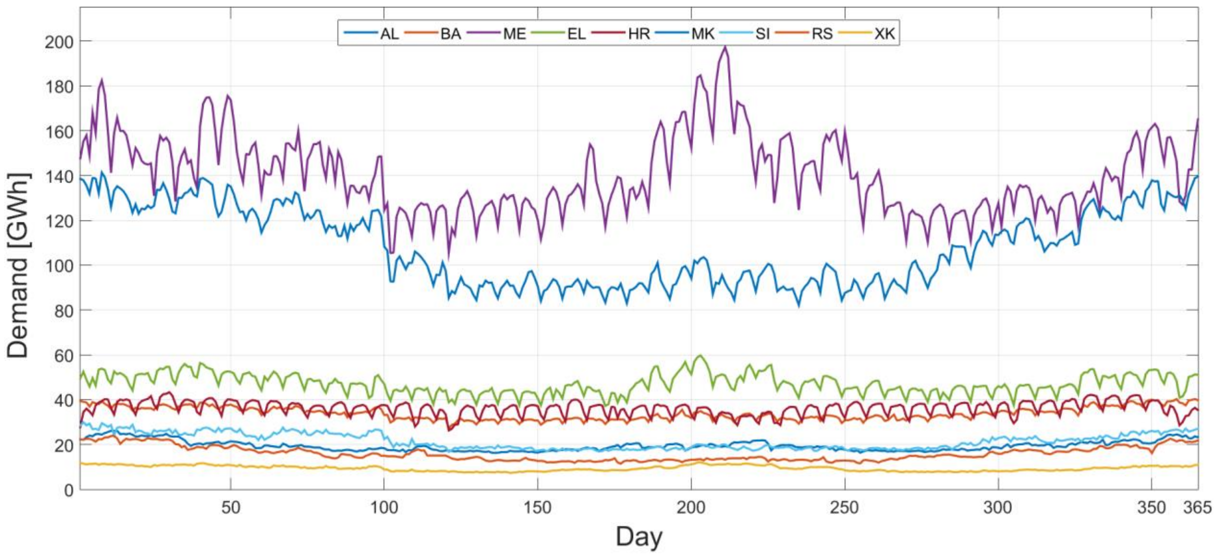



**Figure 5.1. Demand profiles of the studied countries for the year 2015**

The average demand for the Albania, Bosnia and Herzegovina, Montenegro, Greece, Croatia, North Macedonia, Slovenia, Serbia and Kosovo in year 2015 was 19.42, 33.88, 9.37, 140.62, 47.1, 21.47, 36.24, 108.23 and 15.85 GWh, respectively, while the maximum demand peaked at 26.11, 40.26, 12.07, 197.28, 59.69, 29.92, 43.31, 141.3 and 23.89 GWh/day, respectively.

### 5.1.3. *Water inflows*

Net water inflows have been provided by the JRC from the rainfall-runoff hydrological LISFLOOD model briefly described in Section 4.1. The assumption is that the provided water inflows are the total runoff at studied catchment level. Figure 5.2. represents the total sum of inflows for the included hydropower plant locations for the period between 1990 and 2016. The yellow highlighted line represents the runoff for the dry, green highlighted for the average and red for the wet year. The wet, average and dry years are 2010, 2015 and 2007, respectively. The average runoff values for wet, average and dry years are 16,630, 12,248 and 10,447 $m^3/s$, respectively, while the runoff peaked at 29,469, 19,975 and 19,057, respectively.

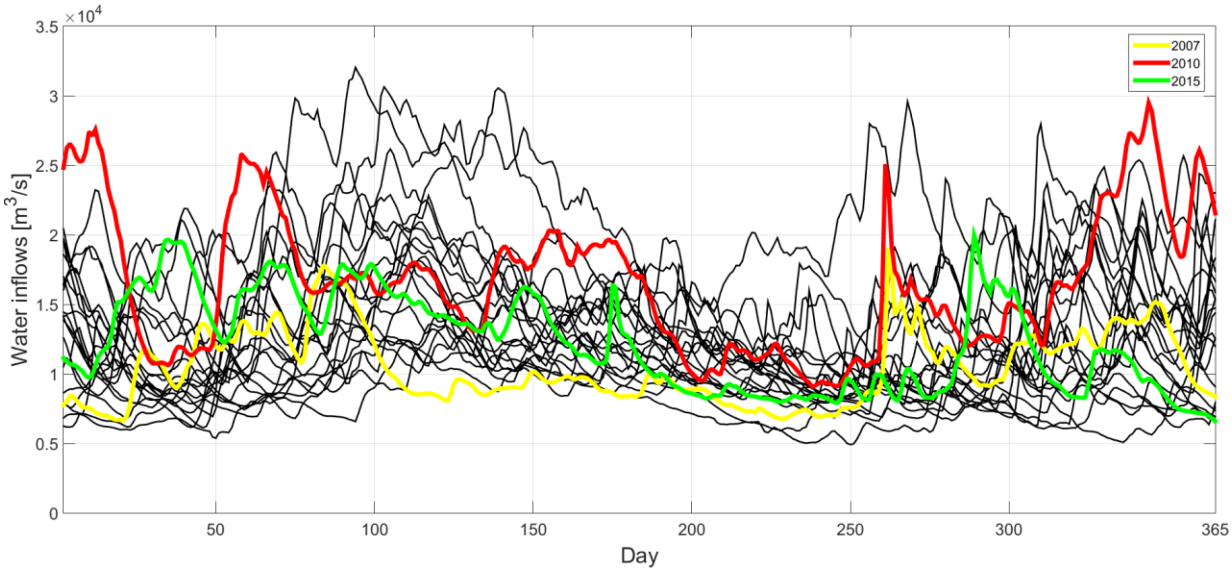



**Figure 5.2. The total sum of the water inflows for the studied region between 1990 and 2016, [71]**

### 5.1.4. *Wind and solar power profiles*

Wind and solar power capacities for the reference year were studied. The wind power capacities are present in Greece, Croatia, North Macedonia and Slovenia, with a total installed power capacity of 1,613, 429, 35 and 3 MW, respectively. The solar power capacities are present in Greece, Croatia and Slovenia, with a total installed power capacity of 2,429, 44 and 262 MW, respectively. Data on total installed power capacity for the solar and wind power was obtained from ENTSO-E Transparency Platform.[61]

Data on power generation from solar power plants was obtained from Strategic Energy Technologies Information System (SETIS), from EMHIRES dataset in the form of capacity factors.[99]

Data on power generation from wind power plants was obtained from Renewables ninja dataset in the form of capacity factors.[100]

Figure 5.3 represents yearly capacity factor values for the solar power plants in Greece, Croatia and Slovenia, while Figure 5.4. shows yearly capacity factor values for the wind power plants in Greece, Croatia, North Macedonia and Slovenia.

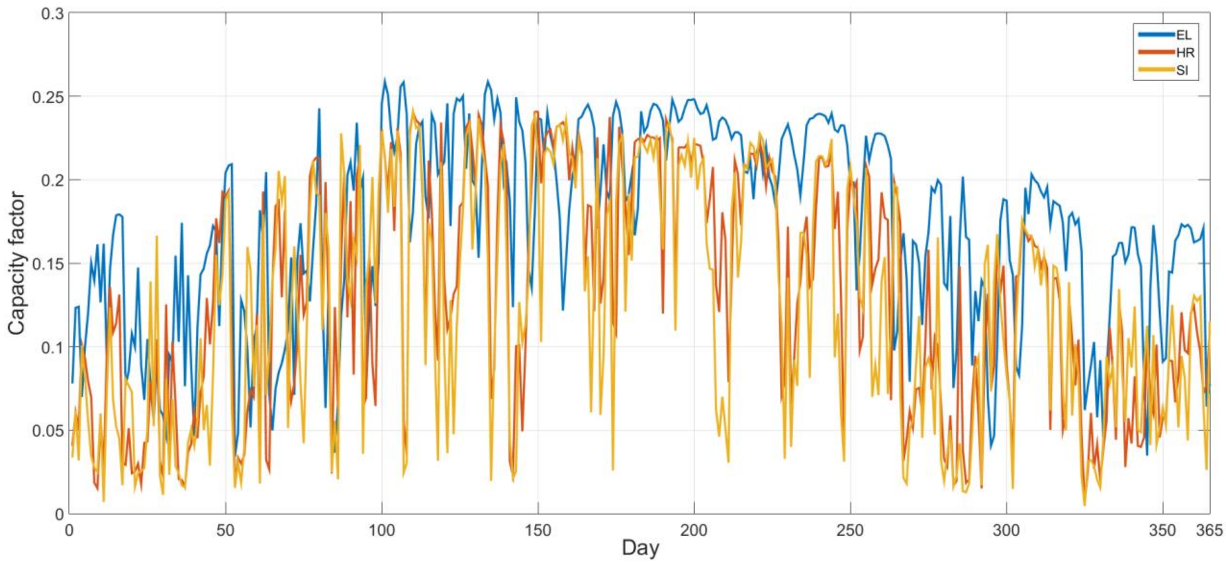



**Figure 5.3. Capacity factor values of solar power plants in Greece, Croatia and Slovenia for the year 2015**

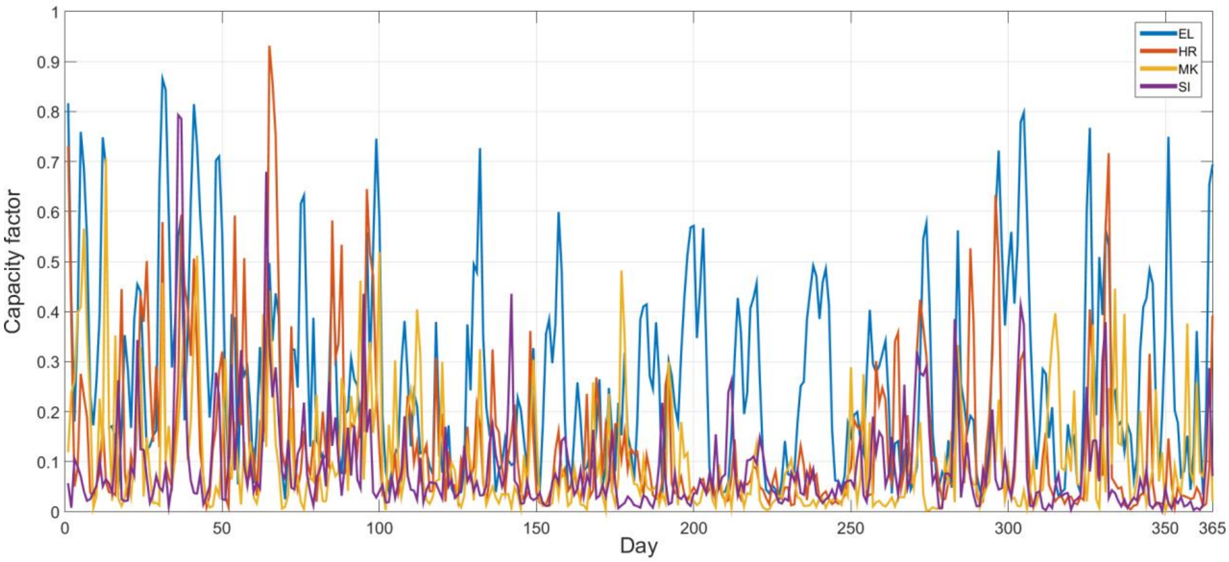



**Figure 5.4. Capacity factor values of wind power plants in Greece, Croatia, North Macedonia, Slovenia for the year 2015**

### 5.1.5. *Line capacities*

Data on line capacities was covered in the form of Net Transfer Capacities (NTC). Data was obtained from a thoroughly made study on NTC values for the studied region which covered three different ways of calculating the NTC values.[101] The first case included all network elements 400, 220 and 200 kV. In the second case only 400 and 220 kV network elements were covered, and in the case three, only tie-lines were monitored. Data on NTC values for Kosovo is missing, so they were obtained from [55]. Data from the third scenario were selected as valid NTC values and can be seen in Table 5.6.

**Table 5.6. NTC Values for the studied region in MW, [56],[101]**

| Import | Export | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AL | BA | BG | HR | MK | ME | RO | RS | SI | XK | IT | AT | HU | UA | TR | EL |
| AL | | / | / | / | / | 430 | / | 327 | / | 550 | / | / | / | / | / | 683 |
| BA | / | | / | 1076 | / | 1,088 | / | 1,278 | / | / | / | / | / | / | / | / |
| BG | / | / | | / | 412 | / | 1,814 | 745 | / | / | / | / | / | / | 1,684 | 987 |
| HR | / | 569 | / | | / | / | / | 1,078 | 880 | / | / | / | 2,597 | / | / | / |
| MK | / | / | 1,185 | / | | / | / | 870 | / | 440 | / | / | / | / | / | 636 |
| ME | 383 | 746 | / | / | / | | / | 534 | / | 440 | / | / | / | / | / | / |
| RO | / | / | 891 | / | / | / | | 999 | / | / | / | / | 1,924 | 2,280 | / | / |
| RS | 671 | 731 | 1,635 | 669 | 441 | 311 | 830 | | / | 680 | / | / | 872 | / | / | / |
| SI | / | / | / | 1,402 | / | / | / | / | | / | 893 | 1,645 | / | / | / | / |
| XK | 671 | / | / | / | 440 | 440 | / | 680 | / | | / | / | / | / | / | / |
| IT | / | / | / | / | / | / | / | / | 774 | / | | n.a. | / | / | / | 500 |
| AT | / | / | / | / | / | / | / | / | 1,162 | / | n.a. | | n.a. | / | / | / |
| HU | / | / | / | 789 | / | / | / | 1,401 | / | / | / | n.a. | | n.a. | / | / |
| UA | / | / | / | / | / | / | / | / | / | / | / | / | n.a. | | / | / |
| TR | / | / | 1,457 | / | / | / | / | / | / | / | / | / | / | / | | 913 |
| EL | 440 | / | 1,693 | / | 879 | / | / | / | / | / | 500 | / | / | / | 2,260 | |

### 5.1.6. *Topology*

Topology defines the hydropower plants network. It is used for the model to determine upstream inflow for the hydropower plants that utilize the same river water resources.

The topology covered in this study, in form where first mentioned hydropower unit is the upstream one, is mentioned below, where hydropower plants with * are absent from the model due to missing data on water inflow:

- HE Gojak → HE Lesce
- HE Golubic + mHE Krcic → HE Miljacka → HE Jaruga
- HE Peruca + HE Orlovac → HE Dale → HE Zakucac + HE Kraljevac
- HE Rama → HE Jablanica → HE Grabovica → HE Salakovac → HE Mostar*
- HE Trebinje → HE Dubrovnik
- HE Uvac → HE Kokin Brod

- HE Kokin Brod + HE Piva + HE Potpec → HE Visegrad → HE Bajina Basta → HE Zvornik
- HE Bocac → HE Jajce 1* → HE Jajce 2*
- HE Moste → HE Mavcice → HE Medvode → HE Vrhovo → HE Bostanj → HE Blanca → HE Krsko
- HE Doblar → RHE Avche → HE Plave → HE Solkan
- HE Dravograd → HE Vuzenica → HE Vuhred → HE Ozbalt → HE Fala → HE Mariborski Otok → HE Zatolicje → HE Formin → HE Varazdin → HE Cakovec → HE Dubrava
- HE Globacica → HE Shpilje → HE Fierza → HE Komani → HE Vau Dejes → HE Ashta*
- HE Kozjak → HE Sveta Petka
- RHE Thisavros → HE Platanovrisi
- HE Ilarionas → HE Polyphyton → HE Sfikia → HE Asomata
- HE Pigai Aoos → HE Pournari 1 → HE Pournari 2
- HE Plastira → HE Kremasta → HE Kastraki → HE Stratos
- HE Agras → HE Edessaios

### 5.1.7. *Water demand*

Water demand can be divided into water used for hydropower production, water used for cooling thermal power plants and water used for other non energy-related purposes like agriculture, irrigation industry, drinking water supply etc. Due to the lack of data on water withdrawal and water consumption besides the hydropower generation, other water withdrawal and consumption activities mention above were taken in account through minimum amount of water reservoir level set to 20% of maximum reservoir level for each hydropower unit with accumulation. Data on water withdrawal and consumption for other activities than the hydropower generation is quite important and it will be included in the future work, so the water-energy nexus could be investigated in more detail.

## 5.2. Dispa-SET Unit Commitment and Dispatch Input Data

In the next few sections, only data additionally needed, that is not covered in Section 5.1, will be mentioned.

### 5.2.1. *Power plants*

Additionally to data covered in Section 5.1.1, common fields needed for all units are shown in Table 5.7. All data related to power plants for the Dispa-SET UTC were obtained from [45] and [55], with the addition of power plants data for Greece from [2].

Additionally, related to storage units, some parameters must be added and are show in Table 5.8.[77]

For the CHP units additional data, dependent on CHP type, is needed as input. Types of CHP covered in Dispa-SET UCD are extraction/condensing, backpressure and power-to-heat units. Additional data with the description, field name and units are shown in Table 5.9. In Table 5.10., mandatory fields based on the CHP type are shown.[77]

**Table 5.7. Common fields needed for all units, [77]**

| Description | Field name | Units |
|---|---|---|
| Unit name | Unit | |
| Commissioning year | Year | |
| Technology | Technology | |
| Fuel | Primary fuel | |
| Zone | Zone | |
| Capacity | PowerCapacity | MW |
| Efficiency | Efficiency | % |
| Efficiency at minimum load | MinEfficiency | % |
| $CO_2$ intensity | CO2Intensity | $TCO_2$/MWh |
| Minimum load | PartLoadMin | % |
| Ramp up rate | RampUpRate | %/min |
| Ramp down rate | RampDownRate | %/min |
| Start-up time | StartUpTime | h |
| Minimum up time | MinUpTime | h |
| Minimum downtime | MinDownTime | h |
| No load cost | NoLoadCost | €/h |
| Start-up cost | StartUpCost | € |
| Ramping cost | RampingCost | €/MW |
| Presence of CHP | CHP | y/n |

**Table 5.8. Additional storage specific fields, [77]**

| Description | Field name | Units |
|---|---|---|
| Storage capacity | STOCapacity | MWh |
| Self-discharge rate | STOSelfDischarge | %/h |
| Maximum charging power | STOMaxChargingPower | MW |
| Charging efficiency | STOChargingEfficiency | % |

**Table 5.9. Additional specific fields for CHP units, [77]**

| Description | Field name | Units |
|---|---|---|
| CHP Type | CHPType | Extraction/back-pressure/p2h |
| Power-to-heat ratio | CHPPowerToHeat | |
| Power loss factor | CHPPowerLossFactor | |
| Maximum heat production | CHPMaxHeat | MW(th) |
| Capacity of heat storage | STOCapacity | MWh(th) |
| % of storage heat loss pet | STOSelfDischarge | % |

**Table 5.10. Mandatory fields based on CHP Type, (X: mandatory, ○: optional), [77]**

| Description | Extraction | Backpressure | Power to heat |
|---|---|---|---|
| CHP Type | X | X | X |
| Power-to-heat ratio | X | X | |
| Power loss factor | X | | X |
| Maximum heat production | ○ | ○ | X |
| Capacity of heat storage | ○ | ○ | ○ |
| % of storage heat loss pet | ○ | ○ | ○ |

### 5.2.2. *Power plants outages*

In the current version of Dispa-SET UTC, planned and unplanned outages are not distinguished, and are defined by "OutageFactor" parameter for each unit. The parameter is equal to zero if there are no outages, and one if the unit is out of operation. The data on unit outages were obtained from ENTSO-E Transparency platform and nationally related TSO's web sites, collected in the database [55].[61]

### 5.2.3. *Hydro data*

Additional data needed as input for the Dispa-SET UCD model are results from Dispa-SET MTHC model. Additional data are hydropower production of run-of-river units and reservoir levels of hydropower plants with storage.[77]

Hydropower production of run-of-river units is defined through the availability factor (AF), which has the same definition as the capacity factor for wind and solar power generation. It is described as energy generated in one hour divided by the total installed power of the unit and it ranges from zero to one, depending on the availability of energy source. It is exogenous time series defined for all renewable power generation units, which generated energy cannot be stored and it is fed to the grid or curtailed.[77]

Because of a model tendency to empty reservoir storage at the end of the optimization horizon, due to emptying the storage having zero marginal cost, additional input of reservoir level for the last hour of each horizon is needed. The input to Dispa-SET UCD is defined as a normalized value with respect to the maximum storage capacity, so its minimum value is zero, and the maximum is one.

### 5.2.4. *Power flows*

The power flow between the simulated region and outer zones cannot be modeled endogenously, so it must be provided as exogenous input. Data for this study was obtained from ENTSO-E Transparency Platform [62], and were data were missing, database [55] was used.[77]

# 6. MODEL RESULTS

## 6.1. Results from the Dispa-SET Medium-Term Hydrothermal Coordination model

The study included three different hydrological years. The year 2015 was selected as the reference year, while also representing an average hydrological year. Based on provided water inflows from the LISFLOOD model, the year 2010 and 2007 were selected as a wet and dry hydrological year, respectively. Aggregated water inflows for the studied region can be seen in Figure 5.2., while its average yearly values are 19,057, 19,975 and 29,469 $m^3/s$ for dry, average and wet year, respectively. Water inflows peaked at 10,448, 12,249 and 16,630 $m^3/s$ for dry, average and wet year, respectively.

The Dispa-SET MTHC model was validated based on hydropower production for each country included in the model. The reference year hydropower production was obtained from ENTSO-E Transparency Platform and International Energy Agency (IEA), and compared to the model outputs.[49],[62]

In Table 6.1., the model results for the year 2015, on hydropower production and statistical values from mentioned sources, can be seen.

**Table 6.1. Comparison of hydropower production for average (2015) year,[49],[62]**

| Country | IEA [GWh] | Δ/IEA [%] | ENTSO-E [GWh] | Δ/ENTSO-E [%] | MTHC model [GWh] |
|---|---|---|---|---|---|
| Albania | 5,895 | 0.39 | / | / | 5,918 |
| Bosnia and Herzegovina | 5,551 | 1.23 | 5,650 | -0.55 | 5,619 |
| Greece | 6,150 | 1.77 | 6,091 | 2.76 | 6,259 |
| Croatia | 6,556 | -13.65 | 5,657 | 0.07 | 5,661 |
| Montenegro | 1,491 | -4.96 | 1,415 | 0.14 | 1,417 |
| North Macedonia | 1,865 | -18.34 | 1,514 | 0.59 | 1,523 |
| Serbia | 10,789 | -1.41 | 10,633 | 0.04 | 10,637 |
| Slovenia | 4,091 | -0.12 | 4,060 | 0.64 | 4,086 |
| Kosovo | 140 | 0.36 | / | / | 140.5 |
| Sum | 42,528 | -2.98 | 35,013 | 0.54 | 41,261 |

When model was validated to match hydropower production as equal as possible to the statistically obtained values for the reference year, the model was run for the additional wet and dry years with changed inputs on the water inflows showed in Figure 5.2.

The aggregated yearly hydropower production for the studied region averaged at 95.57, 113.05 and 141.57 GWh, while it peaked at 146.07, 187.64 and 233.92 GWh/day for dry, average and wet year, respectively. Minimum was reached at 52.33, 61.82 and 56.56 GWh/day for the dry, average and wet year, respectively. In Table 6.2. and Table 6.3., total hydropower production of each country and statistically obtained values are shown. The statistical values are not to compare to the model values for the dry and wet years, due to the only input changed being water inflow, while other power generation input data stayed the same as the reference year. Results on yearly region aggregated hydropower generatiom from MTHC model show increase from 34,881 GWh for dry year to 41,261 and 51,668 for average and wet year, respectively. Comparison of the yearly aggregated hydropower production for the studied region can be seen in Figure 6.1., while compared hydropower generation, on a monthly basis for the year 2015, between model results and ENTSO-E data can be seen in Figure 6.2. Comparison shows close relation with statistical data, especially for January, February, July, August and September. Slightly higher differences at -635.31, 354.59 and 335.95 GWh are noticed for May, March and December, respectively.

**Table 6.2. Hydropower production for wet (2010) year,[49],[62]**

| Country | IEA [GWh] | Δ/IEA [%] | ENTSO-E [GWh] | Δ/ENTSO-E [%] | MTHC model [GWh] |
|---|---|---|---|---|---|
| Albania | 7,567 | 8.91 | / | / | 8,241 |
| Bosnia and Herzegovina | 8,026 | -8.95 | 7,870 | -7.14 | 7,308 |
| Greece | 7,485 | -0.17 | 7,457 | 0.20 | 7,472 |
| Croatia | 9,232 | -28.38 | 8,313 | -20.46 | 6,612 |
| Montenegro | 2,750 | -38.73 | 2,738 | -38.46 | 1,685 |
| North Macedonia | 2,431 | -17.85 | 2,316 | -13.77 | 1,997 |
| Serbia | 12,571 | 8.27 | 12,453 | 9.29 | 13,610 |
| Slovenia | 4,703 | -2.42 | 4,249 | 8.00 | 4,589 |
| Kosovo | 156 | -1.07 | / | / | 154.33 |
| Sum | 54,921 | -5.92 | 45,396 | -4.68 | 51,668 |

**Table 6.3. Hydropower production for dry (2007) year,[49],[62]**

| Country | IEA [GWh] | Δ/IEA [%] | ENTSO-E [GWh] | Δ/ENTSO-E [%] | MTHC model [GWh] |
|---|---|---|---|---|---|
| Albania | 2,788 | 76,87 | / | / | 4,931 |
| Bosnia and Herzegovina | 4,001 | 23.04 | 4,001 | 23.04 | 4,923 |
| Greece | 3,376 | 1.81 | 3,367 | 2.08 | 3,437 |
| Croatia | 4,864 | 2.73 | 4,361 | 14.58 | 4,997 |
| Montenegro | 1,284 | 3.82 | 1,292 | 3.17 | 1,333 |
| North Macedonia | 1,010 | -20.02 | 1,054 | -23.36 | 807.75 |
| Serbia | 10,037 | 1.05 | 9,928 | 2.16 | 10,142 |
| Slovenia | 3,266 | 27.89 | 2,814 | 48.44 | 4,177 |
| Kosovo | 94 | 42.21 | / | / | 133.68 |
| Sum | 30,720 | 13.54 | 26,817 | 10.1 | 34,881 |

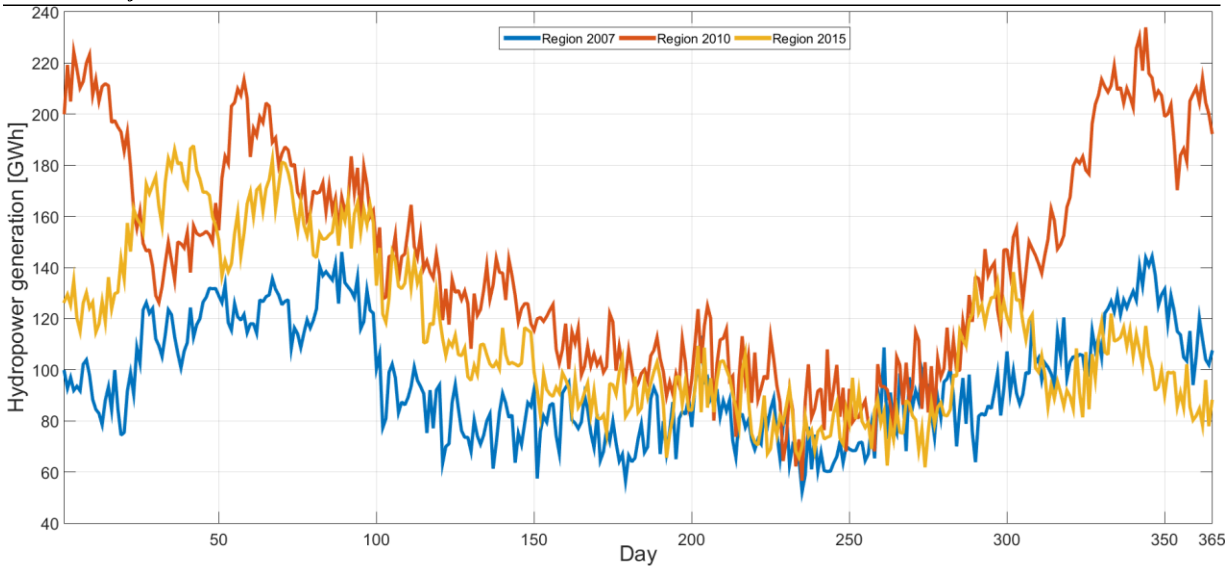



**Figure 6.1. Region aggregated hydropower generation for dry (2007), average (2015) and wet (2015) year, MTHC model**

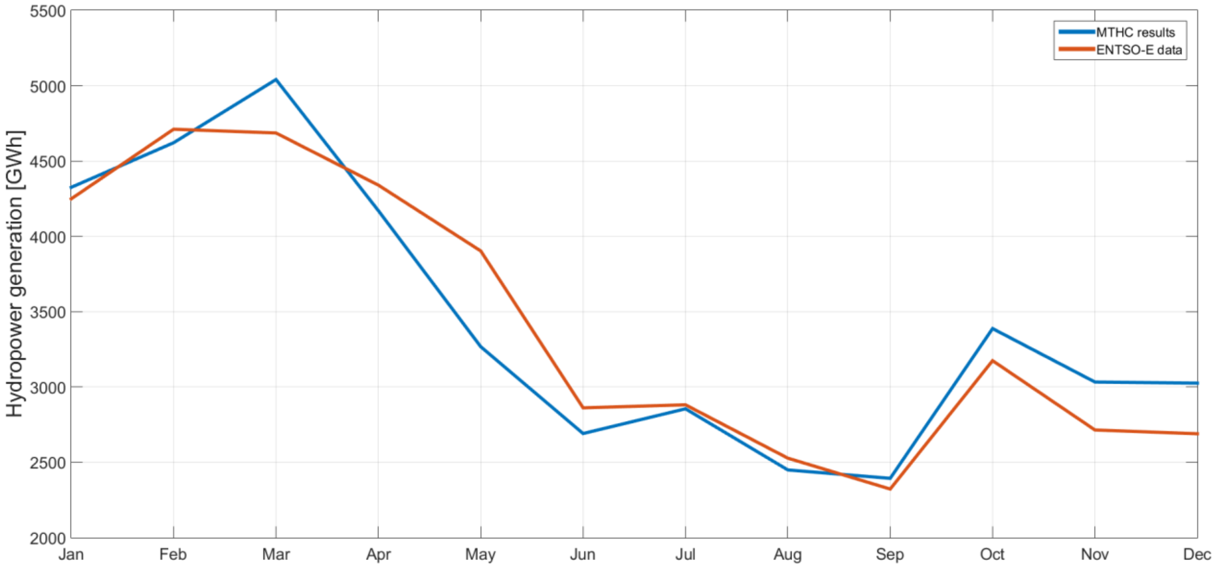



**Figure 6.2. Comparison of region aggregated hydropower generation between MTHC model results and ENTSO-E data for the year 2015**

Reservoir levels and hydropower generation of run-of-river units are vital outputs of the Dispa-SET MTHC model that are needed to successfully run Dispa-SET UTC model.

The average, region aggregated, reservoir level values are 21,951, 22,049 and 23,076 $Mm^3$ for dry, average and wet year, respectively. It reached its peak of 24,634, 25,273 and 26,968 $Mm^3$, while its minimum was at 19,257, 18,888 and 18,690 $Mm^3$ for dry, average and wet year, respectively. The average, minimum, and maximum, aggregated per country, reservoir level values for the dry, average and wet year can be seen in Table 6.4., Table 6.5. and Table 6.6., respectively.

**Table 6.4. Country aggregated reservoir level values for dry (2007) year in Mm3**

| Country | Average | Minimum | Maximum |
|---|---|---|---|
| Albania | 1,600 | 595.84 | 2,936 |
| Bosnia and Herzegovina | 794.7 | 472.65 | 1,186 |
| Greece | 3,075 | 1,769 | 4,110 |
| Croatia | 15,007 | 14,947 | 15,146 |
| Montenegro | 257.94 | 221 | 322.84 |
| North Macedonia | 401.61 | 342.49 | 495.57 |
| Serbia | 565.4 | 285.78 | 729.57 |
| Slovenia | 1.49 | 0.4 | 2 |
| Kosovo | 247.81 | 91.25 | 350 |

**Table 6.5. Country aggregated reservoir level values for average (2015) year in Mm3**

| Country | Average | Minimum | Maximum |
|---|---|---|---|
| Albania | 1,567 | 590.6 | 2,953 |
| Bosnia and Herzegovina | 1,620 | 869.23 | 2,211 |
| Greece | 1,869 | 1,152 | 3,059 |
| Croatia | 15,019 | 14,951 | 15,166 |
| Montenegro | 742.08 | 323.22 | 1,103 |
| North Macedonia | 457.9 | 334.87 | 657.59 |
| Serbia | 502.15 | 287.2 | 687.82 |
| Slovenia | 1.20 | 0.542 | 2 |
| Kosovo | 272.18 | 143.51 | 350 |

**Table 6.6. Country aggregated reservoir level values for wet (2010) year in $Mm^3$**

| Country | Average | Minimum | Maximum |
|---|---|---|---|
| Albania | 1,706 | 590.6 | 2,953 |
| Bosnia and Herzegovina | 1,320 | 453.64 | 2,164 |
| Greece | 2,999 | 1,160 | 4,582 |
| Croatia | 15,072 | 14,938 | 15,255 |
| Montenegro | 630.23 | 221 | 1,105 |
| North Macedonia | 581.39 | 335.55 | 861.13 |
| Serbia | 572.1 | 324.35 | 831.59 |
| Slovenia | 1.42 | 0.547 | 2 |
| Kosovo | 194.16 | 74.42 | 266.14 |

The annual, region aggregated, reservoir level values for the dry, average and wet year can be seen in Figure 6.3.

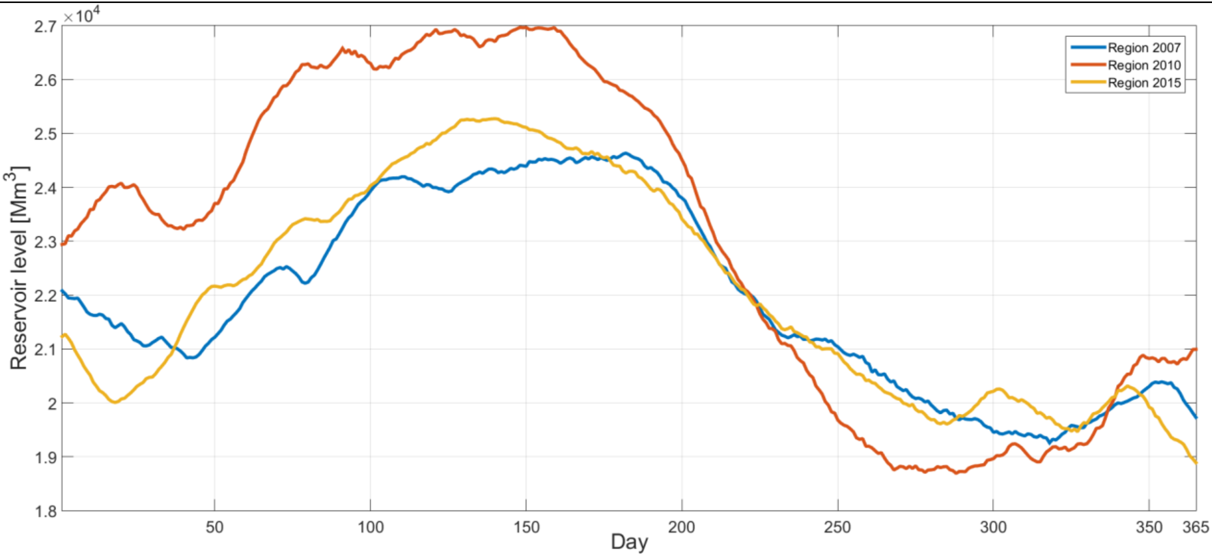



**Figure 6.3. Annual, region aggregated, reservoir level for dry (2007), average (2015) and wet (2010) year in Mm$^3$ as results from the MTHC model**

The availability factor determines run-of-river units hydropower generation and it depends on available water inflows provided from the LISFLOOD model. It is defined as the ratio of available water source power and installed capacity of hydropower unit, but in the next section, it will be expressed as energy produced by run-of-river hydropower units in MWh or GWh.

The yearly average, region aggregated, availability factor values are 34.47, 38.22 and 45.87 GWh, reaching its maximum of 51.33, 51.22 and 62.23 GWh/day for dry, average and wet year, respectively. The run-of-river hydropower generation reached its minimum of 23.68, 23.01 and 29.23 GWh/day for dry, average and wet year, respectively.

It should be stated that only units with a power capacity of more than 10 MW and those provided with water inflows are included in the study, so run-of-river units from Albania, Montenegro, North Macedonia and Kosovo are not included in this study.

The average, minimum, and maximum, aggregated per country, availability values for the dry, average and wet year can be seen in Table 6.7., Table 6.8. and Table 6.9., respectively.

**Table 6.7. Country aggregated availability factor values for dry (2007) year in MWh**

| Country | Average | Minimum | Maximum |
|---|---|---|---|
| Bosnia and Herzegovina | 382.51 | 112.95 | 905.03 |
| Greece | 595.67 | 137.03 | 1,408 |
| Croatia | 5,657 | 4,265 | 7,239 |
| Serbia | 20,901 | 12,349 | 34,636 |
| Slovenia | 6,932 | 3,334 | 12,843 |

**Table 6.8. Country aggregated availability factor values for average (2015) year in MWh**

| Country | Average | Minimum | Maximum |
|---|---|---|---|
| Bosnia and Herzegovina | 482.08 | 111.25 | 1,877 |
| Greece | 839.13 | 224.38 | 1,408 |
| Croatia | 5,881 | 3,836 | 8,864 |
| Serbia | 23,035 | 12,551 | 36,178 |
| Slovenia | 7,978 | 3,850 | 14,682 |

**Table 6.9. Country aggregated availability factor values for wet (2010) year in MWh**

| Country | Average | Minimum | Maximum |
|---|---|---|---|
| Bosnia and Herzegovina | 977.78 | 137.44 | 2,326 |
| Greece | 944.04 | 259.43 | 1,408 |
| Croatia | 5,851 | 3,369 | 8,107 |
| Serbia | 30,189 | 18,888 | 38,128 |
| Slovenia | 7,911 | 3,692 | 12,778 |

The annual, region aggregated availability factor values for the dry, average and wet year can be seen in Figure 6.4.

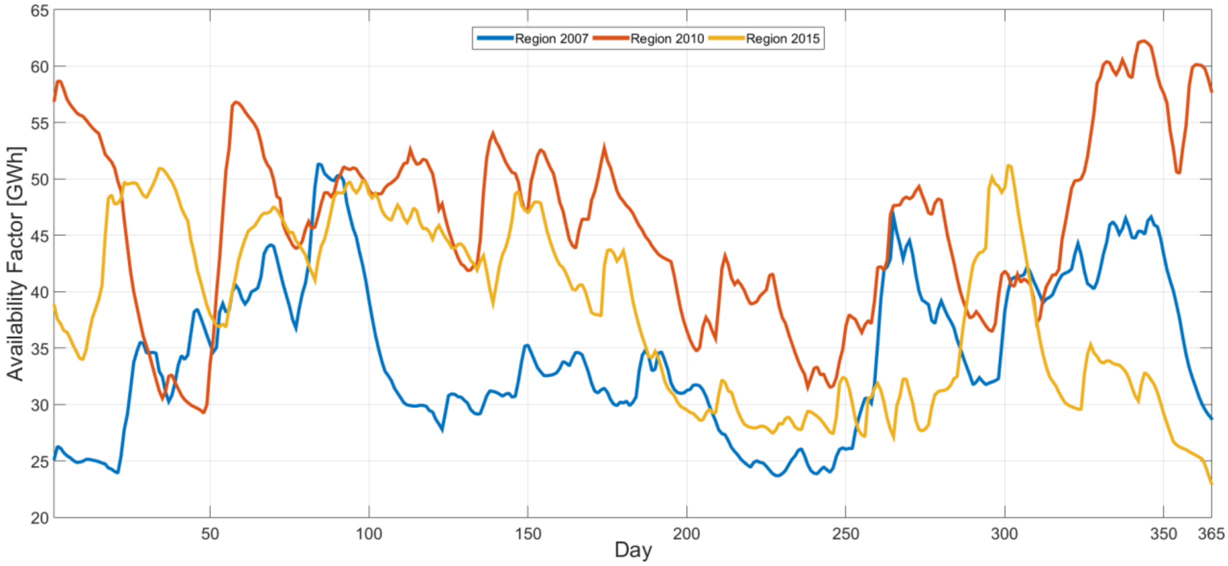



**Figure 6.4. Annual, region aggregated, availability factor values for dry (2007), average (2015) and wet (2010) year in GWh**

Figure 6.5, Figure 6.6 and Figure 6.7 show the power generation, aggregated by fuel, for the average, dry and wet year, respectively as results from MTHC model.

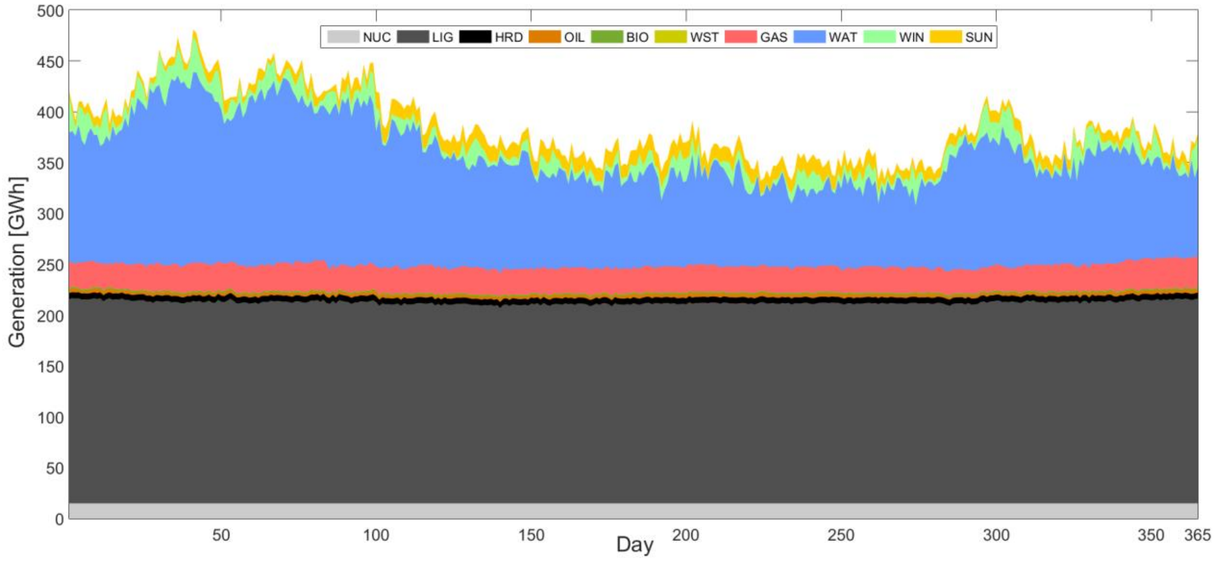



**Figure 6.5. Power generation aggregated by fuel for the average (2015) year in GWh**

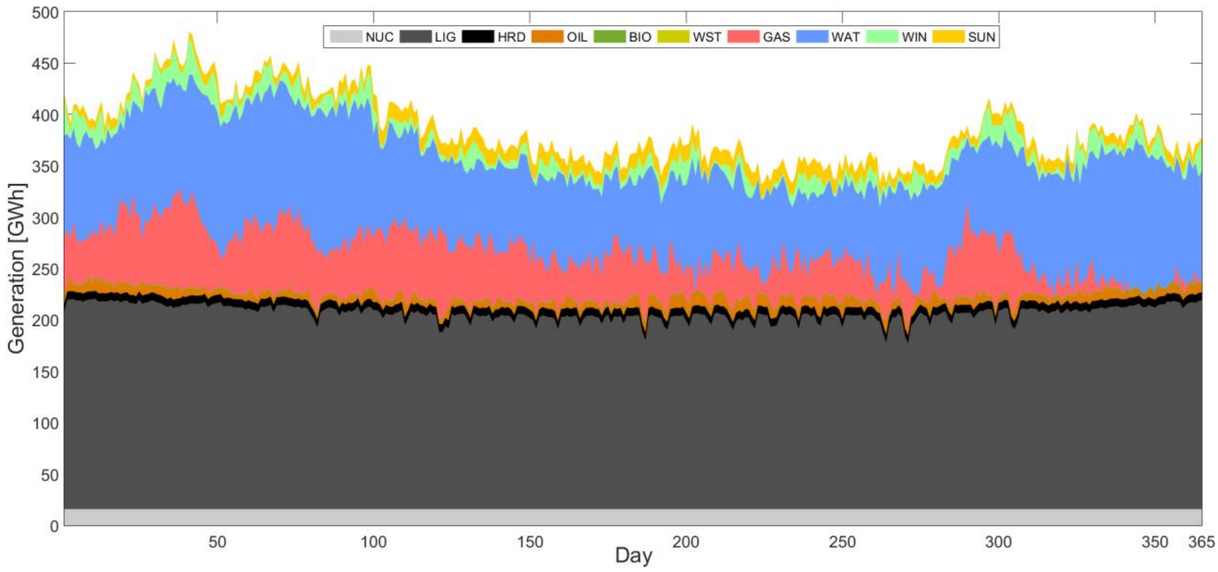



**Figure 6.6. Power generation aggregated by fuel for the dry (2007) year in GWh**

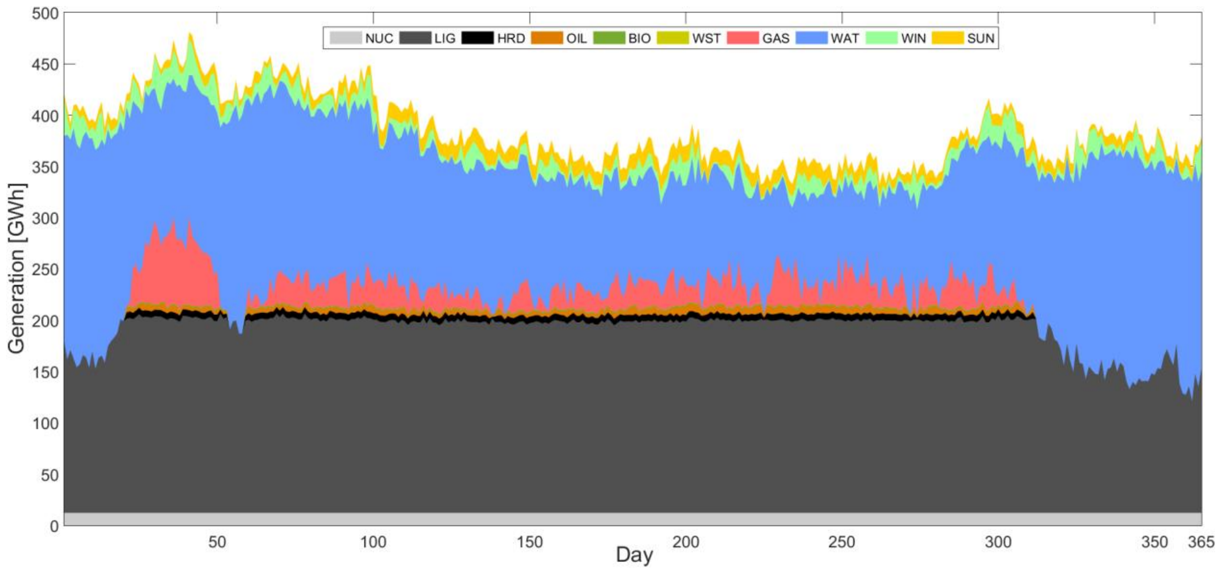



**Figure 6.7. Power generation aggregated by fuel for the wet (2010) year in GWh**

Comparing the power generation figures for an average year with dry and wet years, it can be stated that with higher hydropower generation, other power sources are pushed out of the generation mix. It can be seen that the gas-fired units are covering the shortages of hydropower generation, while at the start and end of the year, even coal-fired units are pushed out. For the dry year scenario, gas units are mostly covering the shortage of hydropower generation.

## 6.2. Results from a Dispa-SET Unit Commitment and Dispatch model

Dispa-SET UCD model was run for the three different hydrological years. Region and country aggregated results will be shown in the next section. Results of the MTHC model were used as inputs for the different scenario models in Dispa-SET UCD model.

Region aggregated results are shown in Table 6.10.

**Table 6.10. Region aggregated results for dry (2007), average (2015) and wet (2010) year**

| Region aggregated statistics | Unit | Dry | Average | Wet |
|---|---|---|---|---|
| Average electricity cost | €/MWh | 21.023 | 17.897 | 17.142 |
| Total consumption | TWh | 157.534 | 157.534 | 157.534 |
| Peak load | GW | 26.751 | 26.751 | 26.751 |
| Net imports | TWh | 17.529 | 17.529 | 17.529 |
| NUC generation | TWh | 5.3787 | 5.3782 | 5.3785 |
| LIG generation | TWh | 91.112 | 86.942 | 75.189 |
| HRD generation | TWh | 2.5262 | 0.1635 | 2.4989 |
| BIO generation | TWh | 0 | 0.0011 | 0.00033 |
| GAS generation | TWh | 1.4738 | 0.1747 | 0.2441 |
| WST generation | TWh | 0.0853 | 0.0896 | 0.08122 |
| SUN generation | TWh | 3.9924 | 3.9924 | 3.9924 |
| WIN generation | TWh | 4.3343 | 4.3343 | 4.3343 |
| WAT generation | TWh | 31.144 | 38.941 | 48.308 |
| Spillage | TWh | 2.124 | 3.899 | 5.530 |
| Start-ups (All units) | No | 5,566 | 25,245 | 10,634 |
| Shutdowns (All units) | No | 5,481 | 25,163 | 10,544 |
| Start-ups (Thermal PP) | No | 249 | 201 | 272 |
| Shutdowns (Thermal PP) | No | 227 | 176 | 253 |

** fuel list related to Dispa-SET supported fuels in documentation [75] and in the list of abbreviations and definitions*

As seen in Table 6.10, the average electricity cost falls with a higher amount of hydropower production followed by a decrease in generation from lignite and gas fired thermal power plants.

Not so notable gap for average electricity cost between average and wet year, as seen between dry and average year, could be explained by higher amount of power generated from hard coal

(15.3 times higher) and gas-fired power plants (1.4 times higher), even though the lignite-fired power plant's generation decreased by 13.52%.

Comparing the number of total and only thermal power plant start-ups and shutdowns, it can be noticed that thermal power units account for only 4.3, 0.75 and 2.48% of total start-ups and shutdowns for dry, average and wet year, respectively. That suggests that mostly hydropower plants account for the total number of start-ups and shutdowns. When comparing a number of start-ups and shutdowns of thermal power plants for a dry and wet year, expected results of a slight increase in total number of start-ups from 249 to 272 and shutdowns from 227 to 253 can be observed. The numbers for average year fall off of expected trend, which could be explained by a number of committed thermal power units with numbers of 36, 31 and 37 for dry, average and wet year, respectively.

Wind and solar generated power is the same across the simulated years, due to the same capacity factor being used as the input data.

Compared hydropower generation between model results and statistical obtained data from [49] and [62], for the year 2015, can be seen in Table 6.11.

**Table 6.11. Comparison of hydropower production for average (2015) year,[49],[62]**

| Country | IEA [GWh] | Δ/IEA [%] | ENTSO-E [GWh] | Δ/ENTSO-E [%] | UCD model [GWh] |
|---|---|---|---|---|---|
| Albania | 5,895 | -20.52 | / | / | 4,685 |
| Bosnia and Herzegovina | 5,551 | -43.87 | 5,650 | -44.86 | 3,116 |
| Greece | 6,150 | 25.29 | 6,091 | 26.5 | 7,705 |
| Croatia | 6,556 | -28.94 | 5,657 | -17.55 | 4,659 |
| Montenegro | 1,491 | 56.84 | 1,415 | 65.26 | 2,339 |
| North Macedonia | 1,865 | -17.1 | 1,514 | 2.12 | 1,546 |
| Serbia | 10,789 | 0.78 | 10,633 | 2.26 | 10,873 |
| Slovenia | 4,091 | -6.39 | 4,060 | -5.68 | 3,830 |
| Kosovo | 140 | 34.79 | / | / | 188.7 |
| Sum | 42,528 | 8.44 | 35,013 | 11.22 | 38,941 |

Results show that, for the most of the countries on a country level results representation, there is a substantial difference between model results and statistical values, which get as high as 56.84 to 65.26% for Montenegro and -43.87 to -44.86% for Bosnia and Herzegovina. Exceptions are results related to Serbia and Slovenia with 0.78 to 2.26% difference and -6.39 to -5.68% difference, respectively. Values on a regional level are summed up close to the statistical values with differences of 8.44 to 11.22%. Hydropower generation on a yearly basis, aggregated by region, can be seen in Figure 6.8. Hydropower generation compared on a monthly basis for the year 2015, between UCD model results and ENTSO-E data can be seen in Figure 6.9.

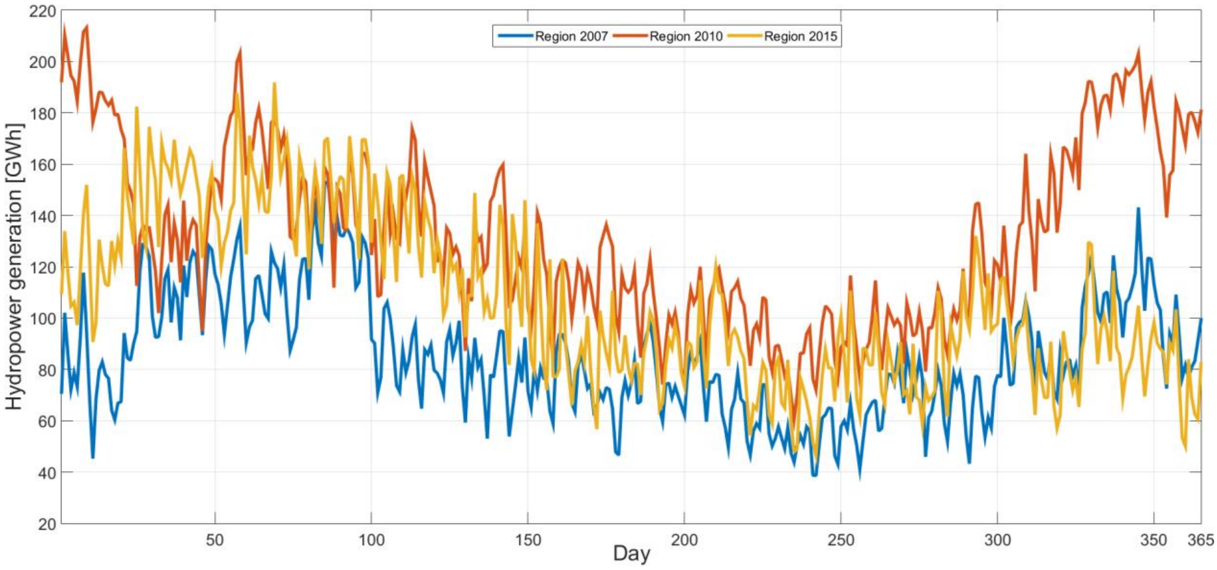



**Figure 6.8. Region aggregated hydropower generation for dry (2007), average (2015) and wet (2015) year, UCD model**

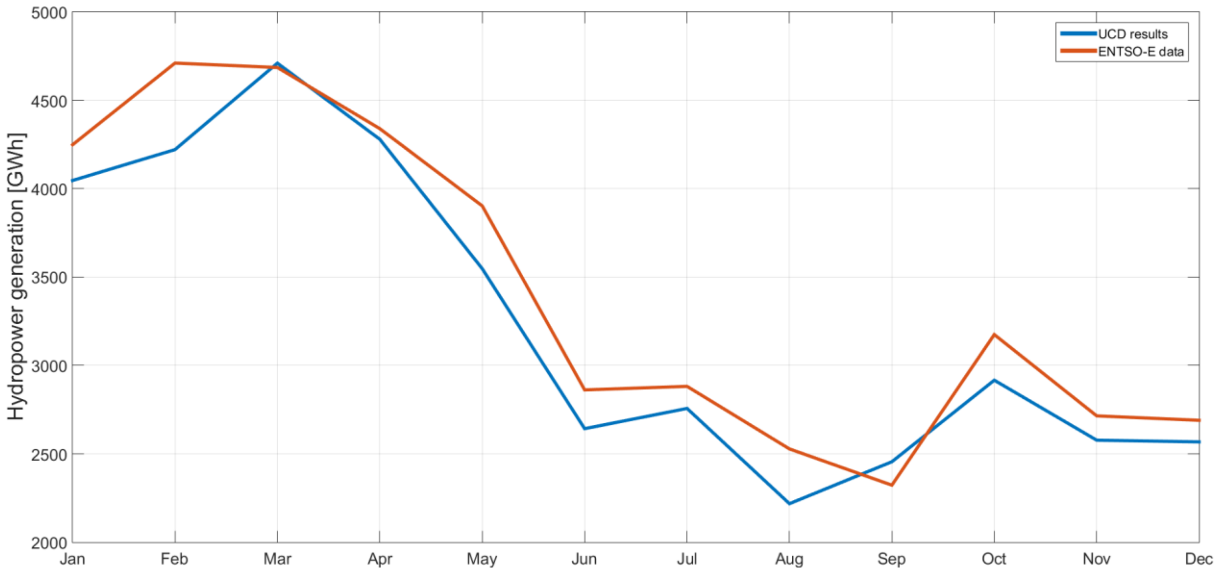



**Figure 6.9. Comparison of region aggregated hydropower generation between UCD model results and ENTSO-E data for the year 2015**

Comparing hydropower generation shown in Figure 6.8., one can state that a higher amount of hydropower generation for a wet year, compared with average, comes from January and later autumn months, November and December. Comparing dry to both wet and average year, it can be seen that hydropower generation for the dry year is mostly below values for wet and average year, with some exceptions of similar hydropower generation for a part of February, and November to December, for dry-wet and dry-average year comparison, respectively.

Comparing model results with ENTSO-E data shown in Figure 6.9, close follow up trend can be noticed with slightly higher differences of -489.63, -388.24 and -309.8 GWh for February, May and August, respectively.

Total hydropower production of each country and statistically obtained values for a dry and wet year are shown in Table 6.12 and Table 6.13, respectively. The statistical values are not to compare to the model values for the dry and wet years, due to the only input changed being water inflow, while other power generation related input data stayed the same as the reference year.

**Table 6.12. Hydropower generation for dry (2007) year,[49],[62]**

| Country | IEA [GWh] | Δ/IEA [%] | ENTSO-E [GWh] | Δ/ENTSO-E [%] | UCD model [GWh] |
|---|---|---|---|---|---|
| Albania | 2,788 | 40.41 | / | / | 3,915 |
| Bosnia and Herzegovina | 4,001 | -31.09 | 4,001 | -31.09 | 2,757 |
| Greece | 3,376 | 21.37 | 3,367 | 21.37 | 4,098 |
| Croatia | 4,864 | -29.66 | 4,361 | -29.66 | 3,421 |
| Montenegro | 1,284 | 49.51 | 1,292 | 49.51 | 1,920 |
| North Macedonia | 1,010 | -33.63 | 1,054 | -33.63 | 670.34 |
| Serbia | 10,037 | 5.06 | 9,928 | 5.06 | 10,545 |
| Slovenia | 3,266 | 5.95 | 2,814 | 5.95 | 3,460 |
| Kosovo | 94 | 281.1* | / | / | 358.28 |
| Sum | 30,720 | 1.38 | 26,817 | 0.2 | 31,144 |

* *due to the big difference between the model result and statistical data, combined with small value number, results with a percentage higher than 100%*

**Table 6.13. Hydropower generation for wet (2010) year [49],[62]**

| Country | IEA [GWh] | Δ/IEA [%] | ENTSO-E [GWh] | Δ/ENTSO-E [%] | UCD model [GWh] |
|---|---|---|---|---|---|
| Albania | 7,567 | -1 | / | / | 7,491 |
| Bosnia and Herzegovina | 8,026 | -31.75 | 7,870 | -30.4 | 5,478 |
| Greece | 7,485 | -5.07 | 7,457 | -4.72 | 7,105 |
| Croatia | 9,232 | -57.75 | 8,313 | -53.07 | 3,901 |
| Montenegro | 2,750 | 3.58 | 2,738 | 4.04 | 2,849 |
| North Macedonia | 2,431 | -21.62 | 2,316 | -17.73 | 1,905 |
| Serbia | 12,571 | 20.47 | 12,453 | 21.61 | 15,144 |
| Slovenia | 4,703 | -13.36 | 4,249 | -0.04 | 4,075 |
| Kosovo | 156 | 130.8* | / | / | 360 |
| Sum | 54,921 | -12.04 | 45,396 | -10.88 | 48,308 |

* *due to the big difference between the model result and statistical data, combined with small value number, results with a percentage higher than 100%*

Total installed power generation capacities can be seen in Figure 6.10, while total power generation, aggregated by fuel for each country, for dry, average and wet year can be seen in Figure 6.11., Figure 6.12. and Figure 6.13., respectively.

Power dispatch and unit commitments for each country are displayed in the appendix.

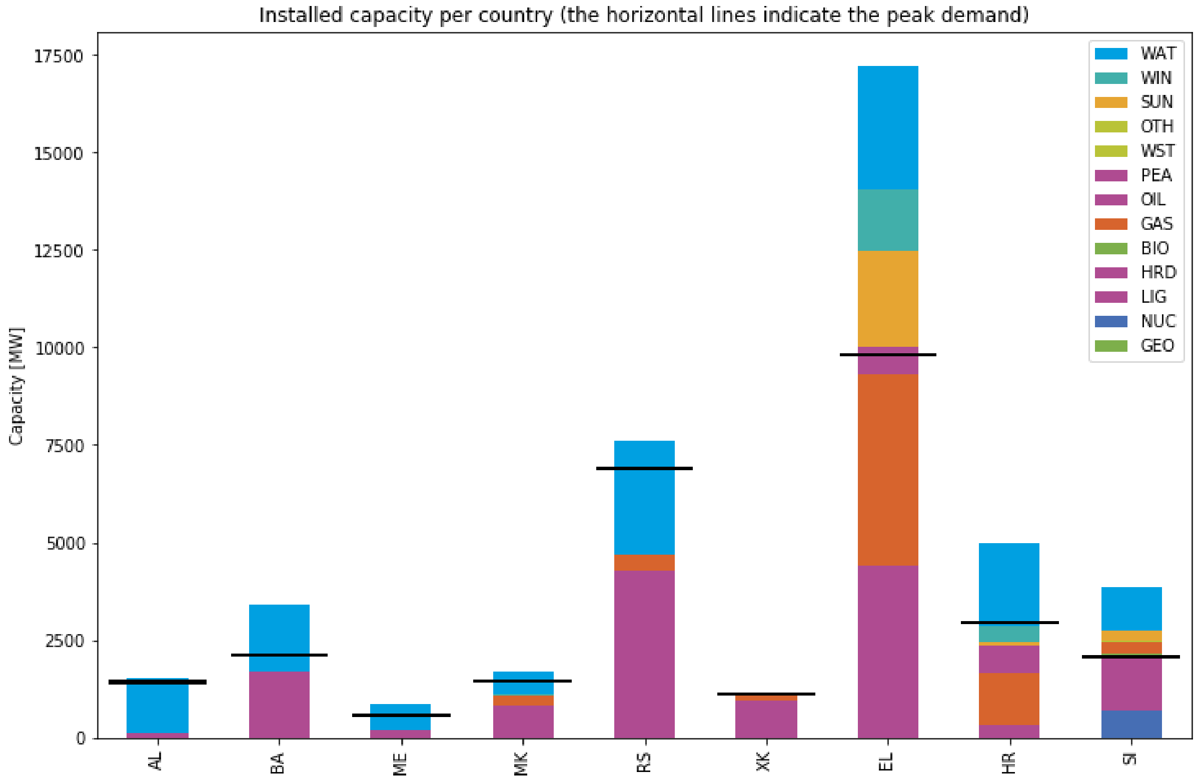



**Figure 6.10. Installed power generation capacities**
*(country and fuel codes are shown in abbreviation and definition list)*

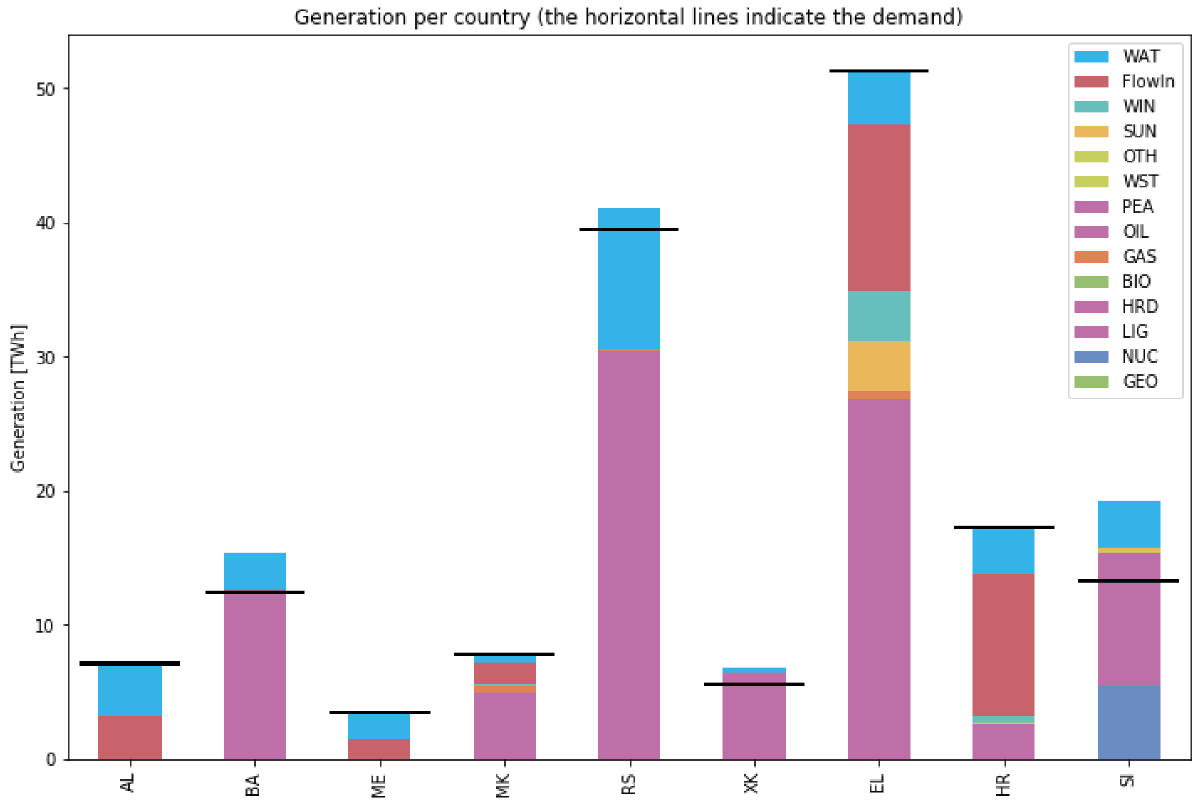



**Figure 6.11. Power generation, aggregated by fuel for dry (2007) year**
*(country and fuel codes are shown in abbreviation and definition list)*

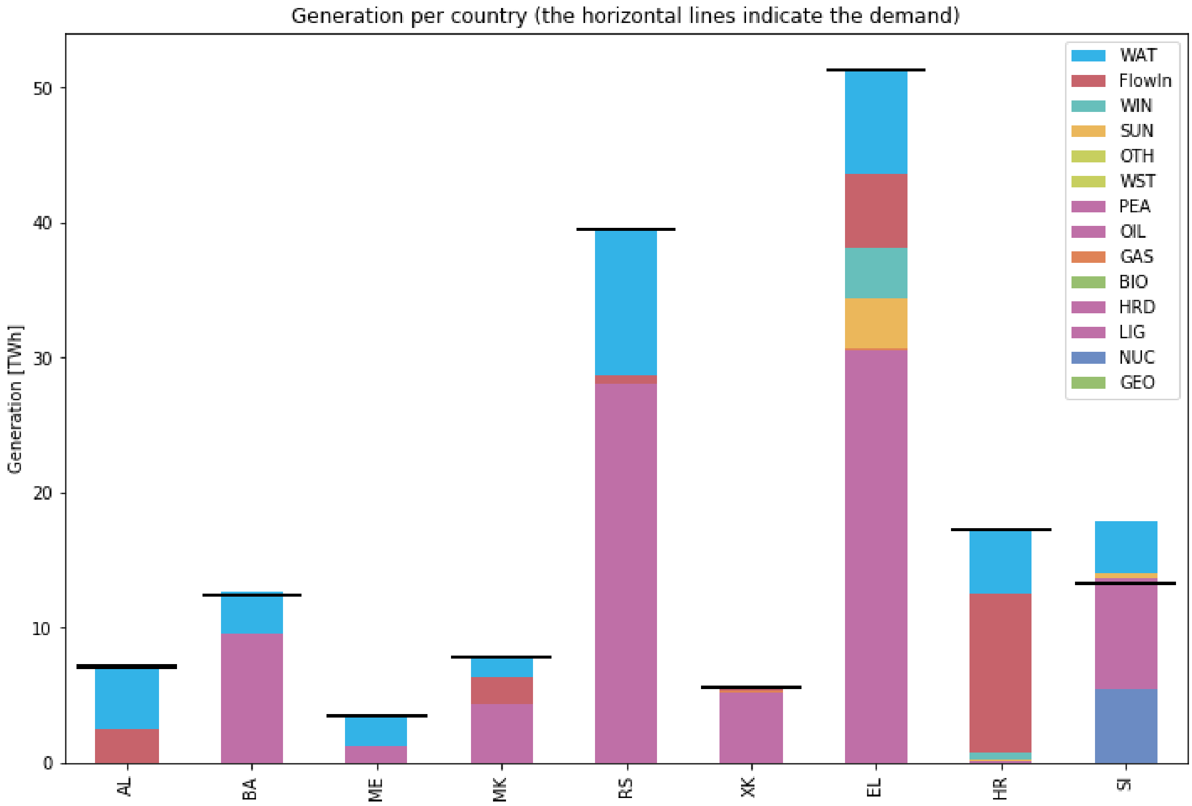



**Figure 6.12. Power generation, aggregated by fuel, for average (2015) year**
*(country and fuel codes are shown in abbreviation and definition list)*

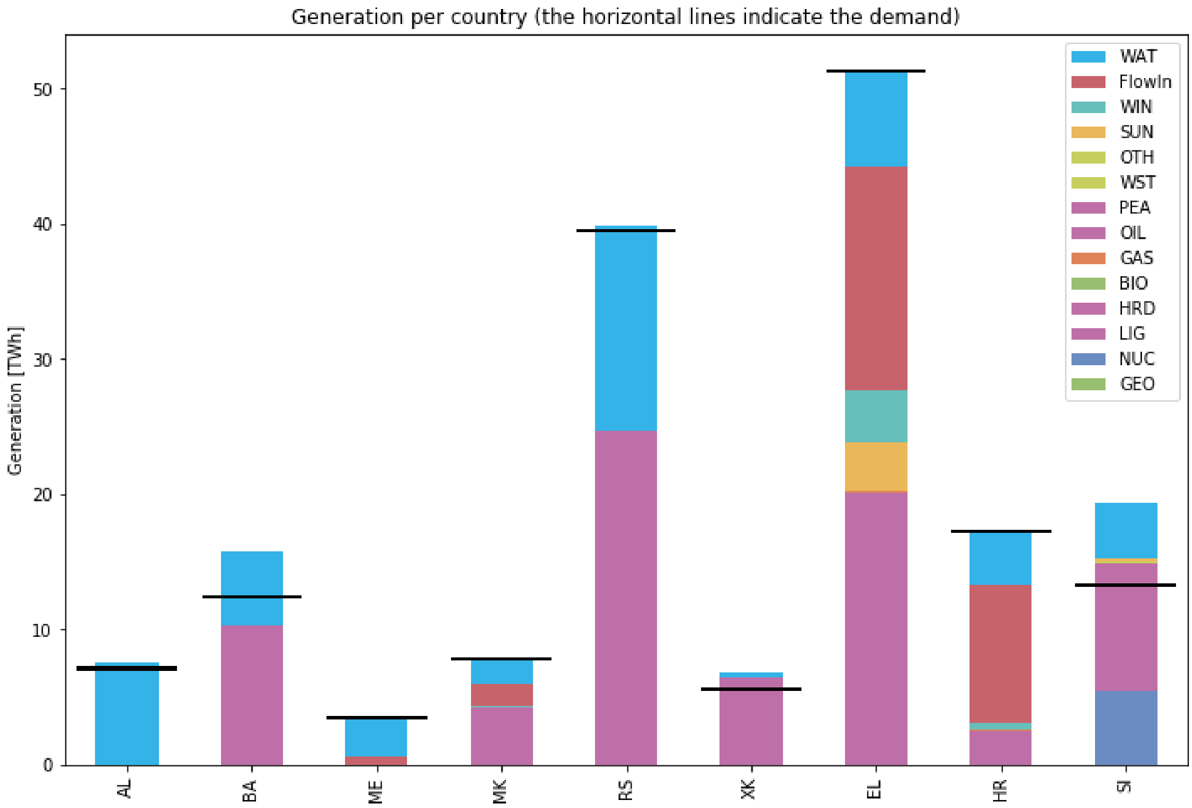



**Figure 6.13. Power generation, aggregated by fuel, for dry (2010) year**
*(country and fuel codes are shown in abbreviation and definition list)*

# 7. CONCLUSION AND FUTURE WORK

This study describes the implementation of three different models for detailed analysis of impacts on the regional power system for different hydrological conditions. Countries included in the study are six Western Balkan countries, Bosnia and Herzegovina, Serbia, Albania, Montenegro, North Macedonia, Kosovo, and three neighboring countries, Croatia, Slovenia and Greece. Combining results in form of water inflows from hydrological model LISFLOOD with Dispa-SET models, three different scenarios for dry, average and wet year were conducted. The first part of the study included gathering data needed for detailed representations of regional power system participants. Data was obtained from multiple sources, mostly from available databases and documentation published by regional TSO's.

Detailed information on hydropower plants data were gathered for Dispa-SET MTHC model. Hydropower generation of run-of-river units and reservoir levels for each hydropower plant with storage are results from the mentioned model needed for unit commitment and dispatch model Dispa-SET UCD. Besides the mentioned results, Dispa-SET MTHC model results include total power generation for each unit included in the model. Yearly region and country aggregated results for the reference year were compared to available statistical data from Internatial Energy Agency and ENTSO-E Transparency platform. Differences between yearly region aggregated statistical data and MTHC model results on hydropower production are -2.98% regarding the IEA data, and 0.54% regarding the ENTSO-E data.

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 of 31.14, 38.94 and 48.31 GWh for dry, average and wet year, respectively, mostly on the expense of a decrease in power generation of lignite and gas-fired power plants. Inversely proportional to increase of hydropower generation, average electricity cost decreased from 21.023 €/MWh for the dry year to 17.879 and 17.142 €/MWh for an average and wet year, respectively. Compared results from UCD model for region aggregated hydropower generation with statistically obtained values show differences of 8.44% regarding the IEA data, and 11.22% regarding the ENTSO-E data.

The individual production of power plants has not been compared to historical data due to several reasons. The MTHC model uses clusters for all powerplants except the hydropower plants, while water inflows have been clustered to a single point if dams are located in the range of 5 km. Moreover, it is hard to obtain the exact production data of certain hydropower plant for referent year so in most cases the average production data are available. A similar problem is present with obtaining the historical measured data on the stored water or water levels in the reservoirs. The UCD model provides more detail on the operation of single power plants but it has not been the main focus of this study. In the future work, it will be necessary to check hundreds of single power plants and their production in order to determine water-power nexus and impacts of different water inflows to the operation of a single powerplant or representative clusters of power plants.

Future work will also include the addition of Hungarian, Bulgarian and Romanian power systems, with the possibility of including the Turkish power system. Also, data on missing hydropower plants for countries included in this study will be available in future work. As previously mentioned in the study, additional data on water withdrawal and consumption for cooling of thermal power units, and water consumption for non-energy purposes is needed for better representation of water-power nexus.

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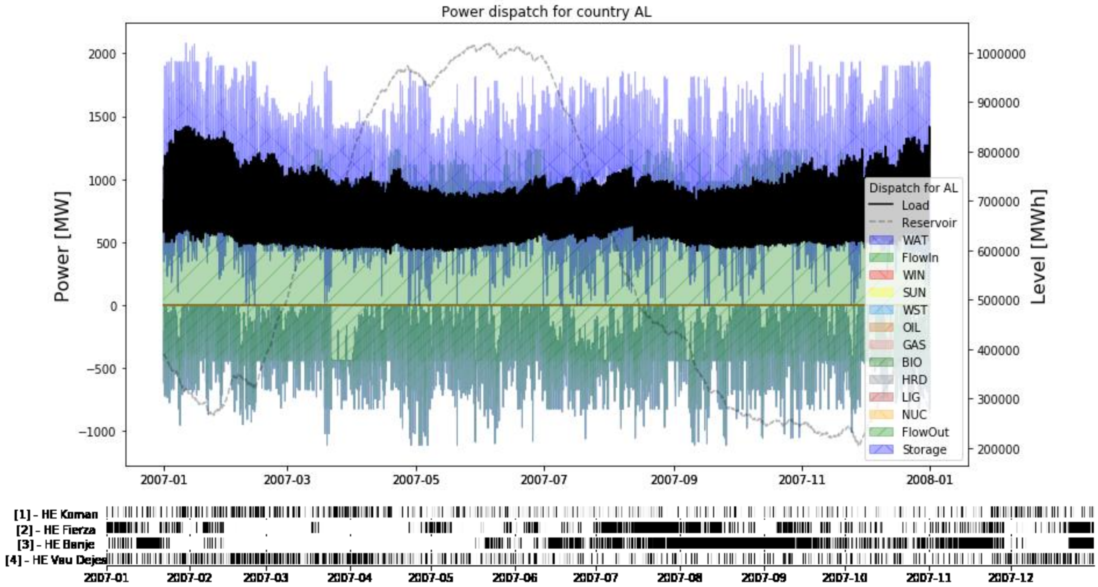
# APPENDIX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Power [MW]
Level [MWh]
Dispatch for AL
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[1] - HE Koman
[2] - HE Fierza
[3] - HE Banje
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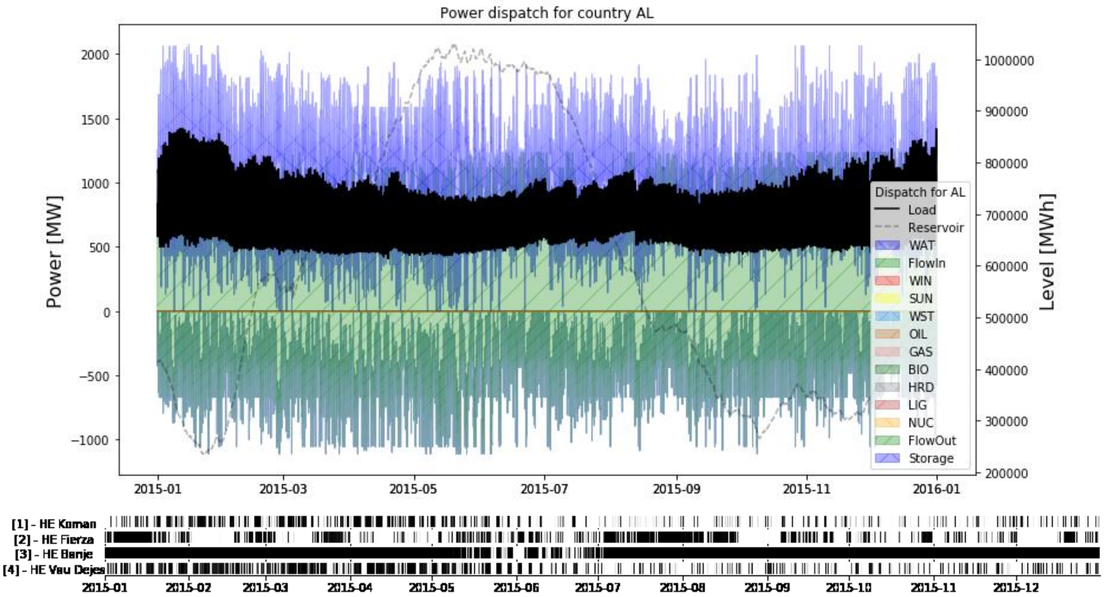
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Power [MW]
Level [MWh]
Dispatch for AL
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
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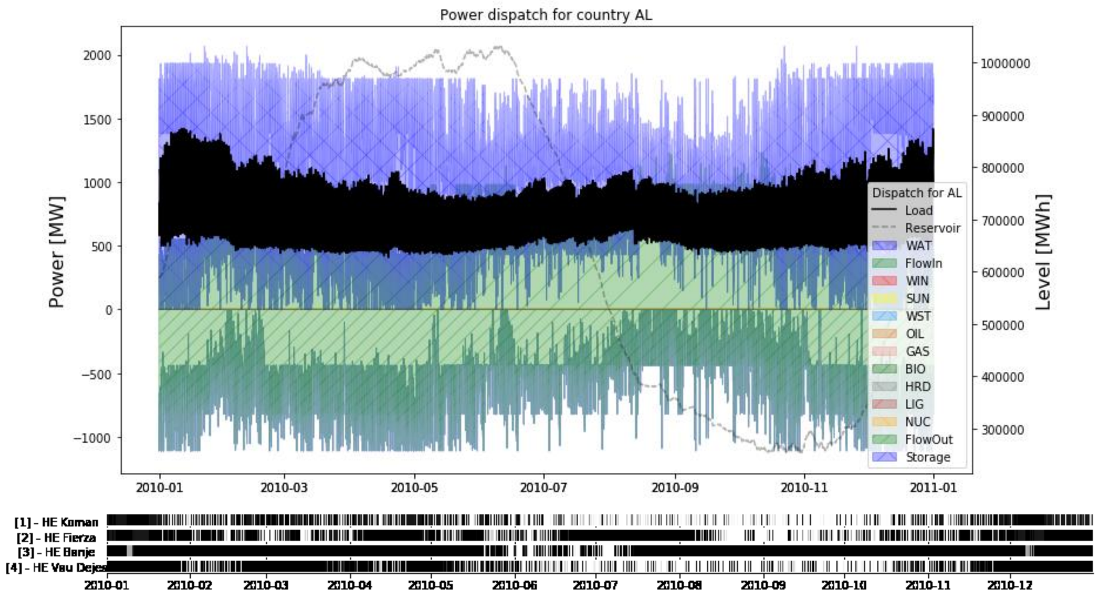
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Power [MW]
Level [MWh]
Dispatch for AL
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
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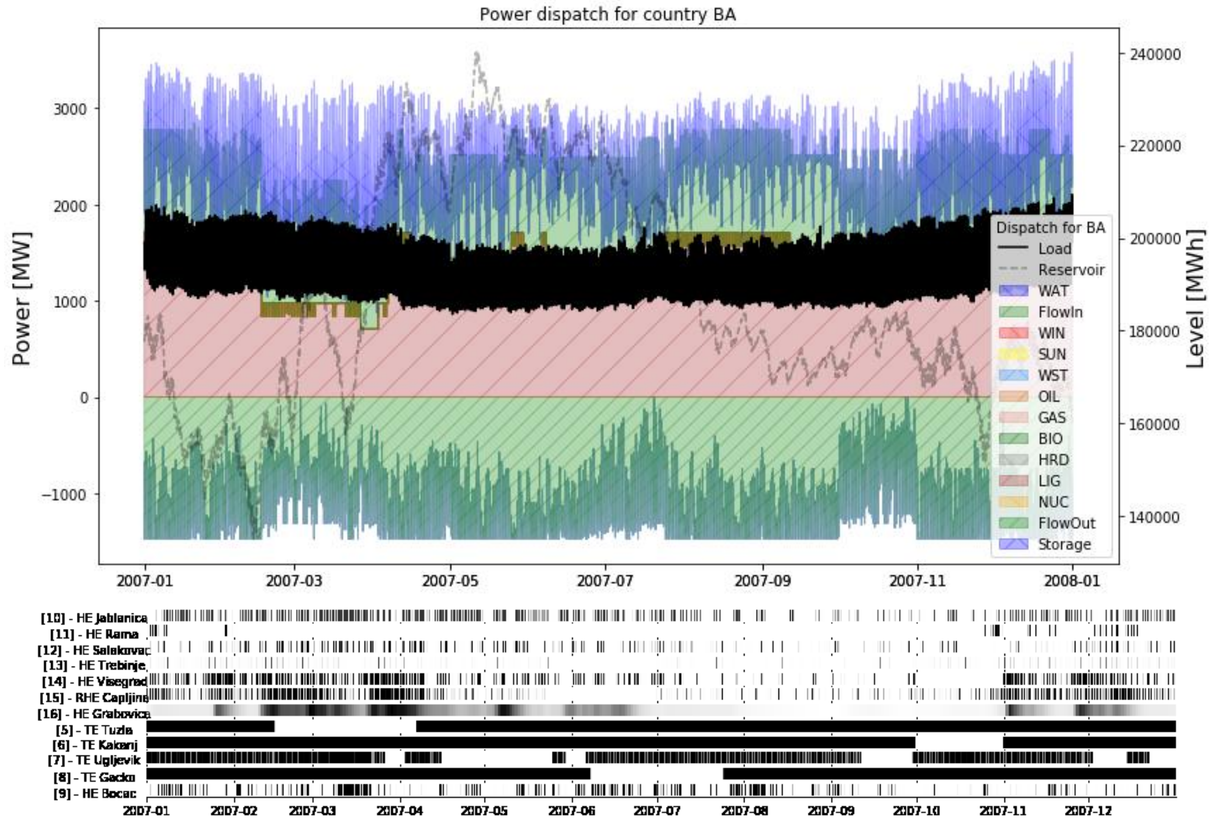
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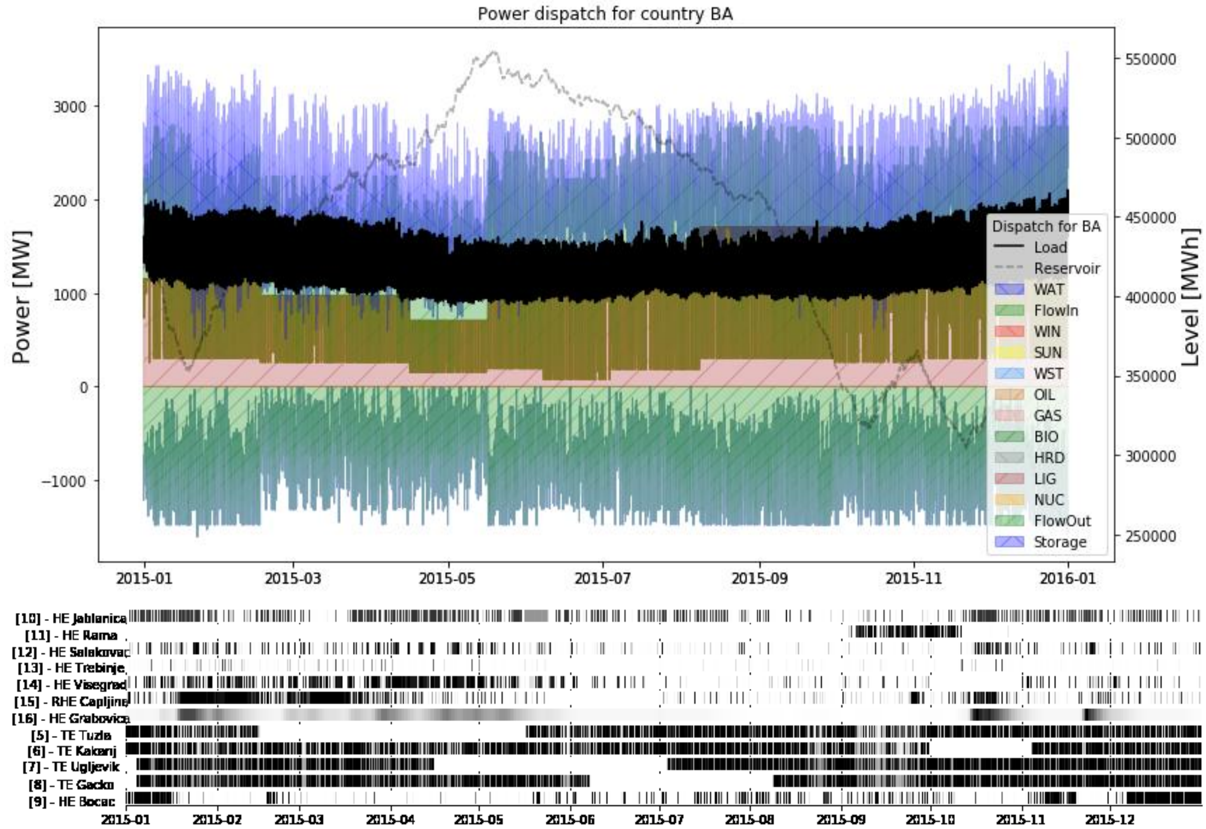
Power [MW]
Level [MWh]
Dispatch for BA
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[10] - HE Jablanica
[11] - HE Rama
[12] - HE Salakovac
[13] - HE Trebinje
[14] - HE Visegrad
[15] - RHE Capljina
[16] - HE Grabovica
[5] - TE Tuzla
[6] - TE Kakanj
[7] - TE Ugljevik
[8] - TE Gacko
[9] - HE Bocac


Power dispatch for country BA
Power [MW]
Level [MWh]
Dispatch for BA
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[10] - HE Jablanica
[11] - HE Rama
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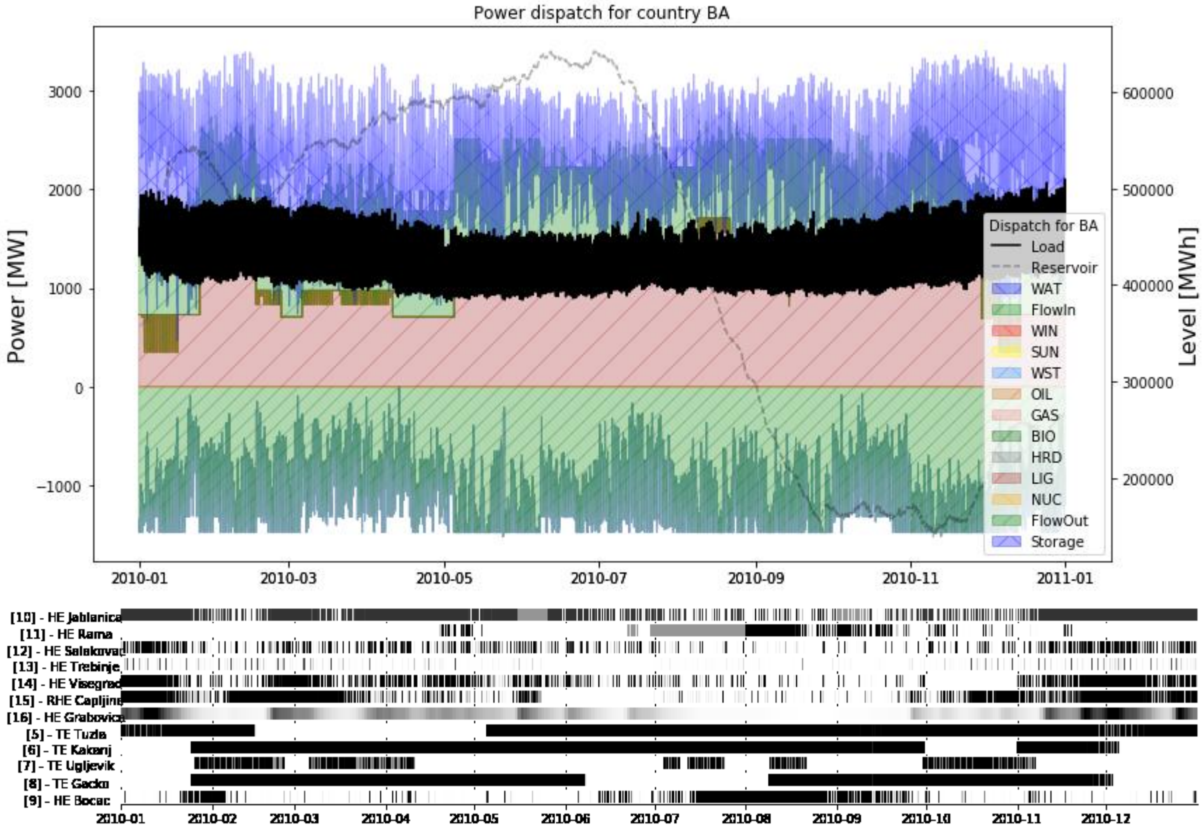
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Power [MW]
Level [MWh]
Dispatch for BA
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[10] - HE Jablanica
[11] - HE Rama
[12] - HE Salakovac
[13] - HE Trebinje
[14] - HE Visegrad
[15] - RHE Capljina
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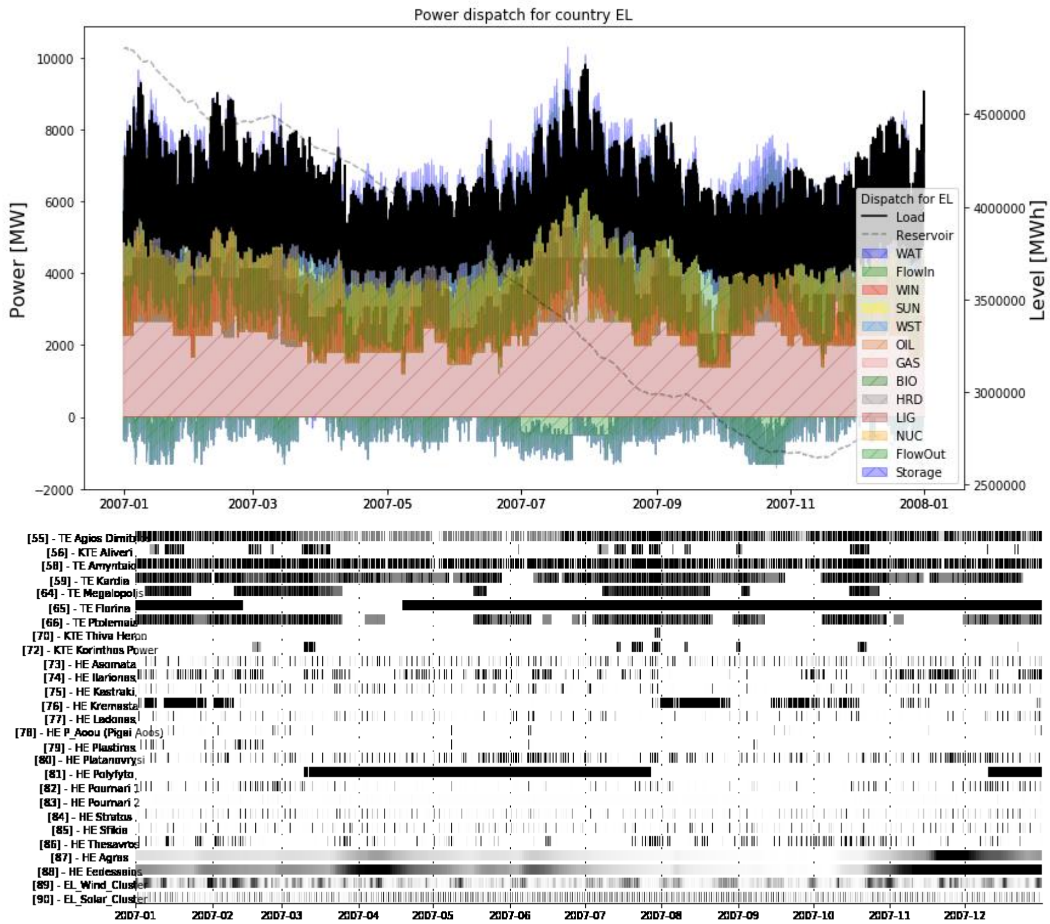
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Power [MW]
Level [MWh]
Dispatch for EL
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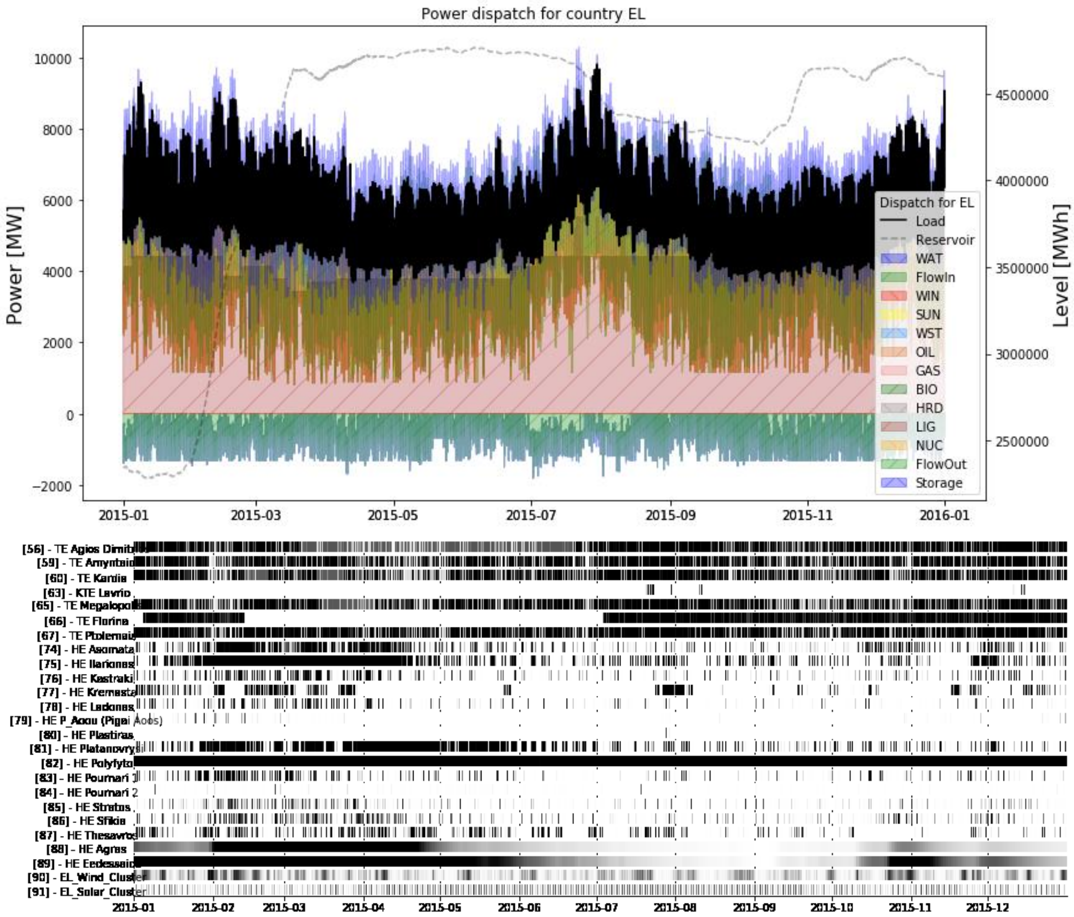
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage


Power dispatch for country EL
Power [MW]
Level [MWh]
Dispatch for EL
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Reservoir
WAT
FlowIn
WIN
SUN
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GAS
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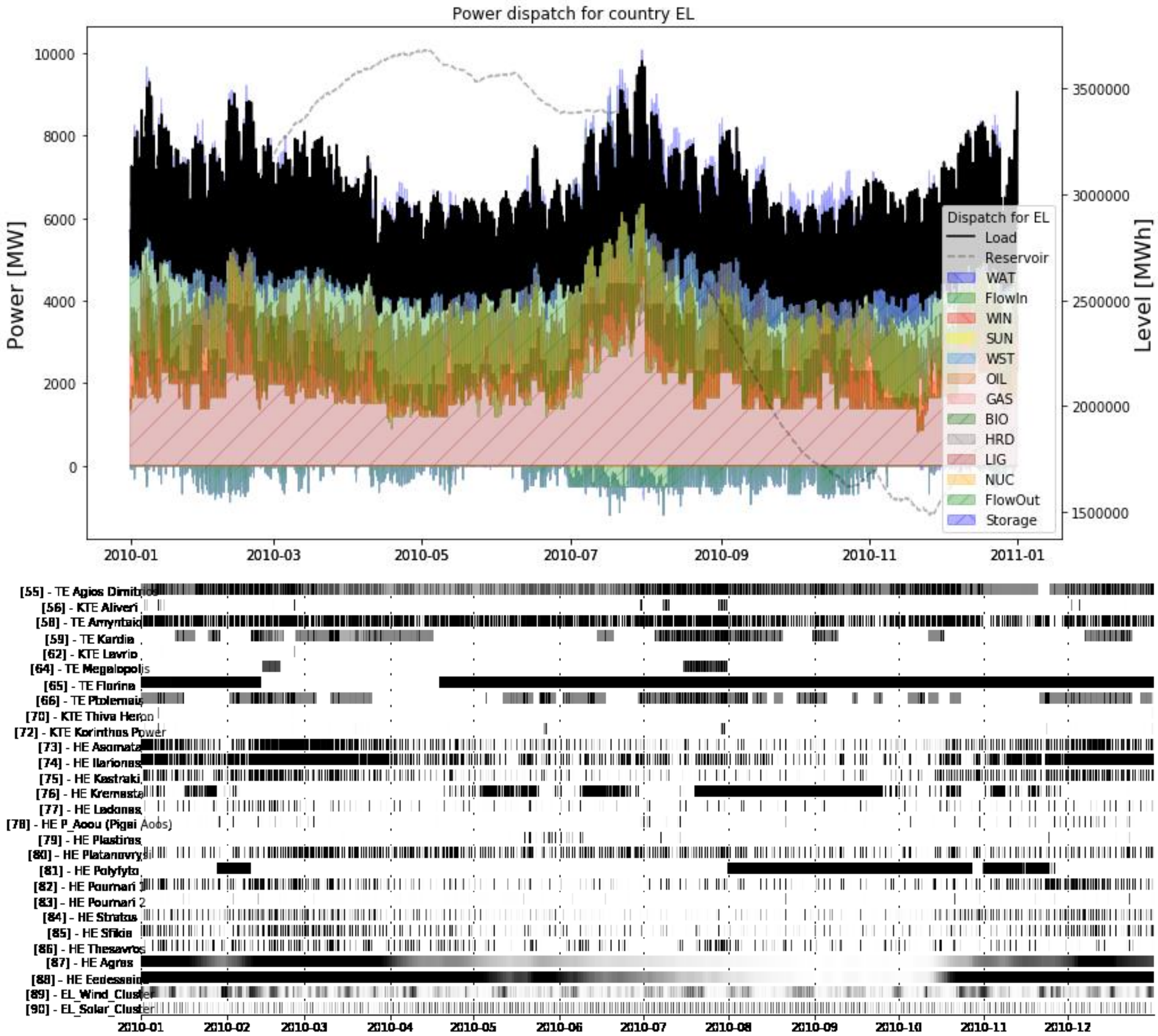
HRD
LIG
NUC
FlowOut
Storage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Power [MW]
Level [MWh]
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8000
6000
4000
2000
0
3500000
3000000
2500000
2000000
1500000
2010-01
2010-03
2010-05
2010-07
2010-09
2010-11
2011-01
Dispatch for EL
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
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[56] - KTE Aliveri
[58] - TE Amyntaio
[59] - TE Kardia
[62] - KTE Lavrio
[64] - TE Megalopolis
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[66] - TE Ptolemais
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[77] - HE Ladonas
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[86] - HE Thesavros
[87] - HE Agras
[88] - HE Eedessaios
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[90] - EL_Solar_Cluster
2010-01
2010-02
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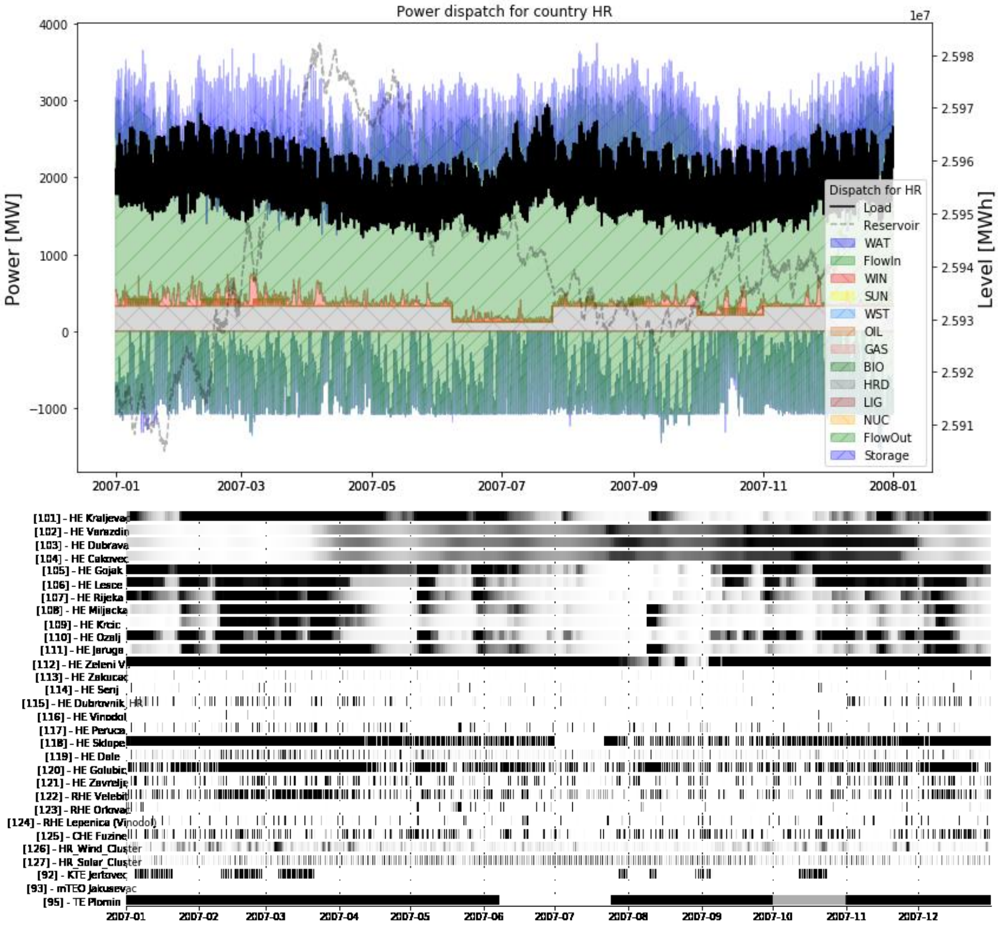
2010-10
2010-11
2010-12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Power [MW]
Level [MWh]
1e7
Dispatch for HR
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
2007-01
2007-03
2007-05
2007-07
2007-09
2007-11
2008-01
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[103] - HE Dubrava
[104] - HE Cakovec
[105] - HE Gojak
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[109] - HE Krcic
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[111] - HE Jaruga
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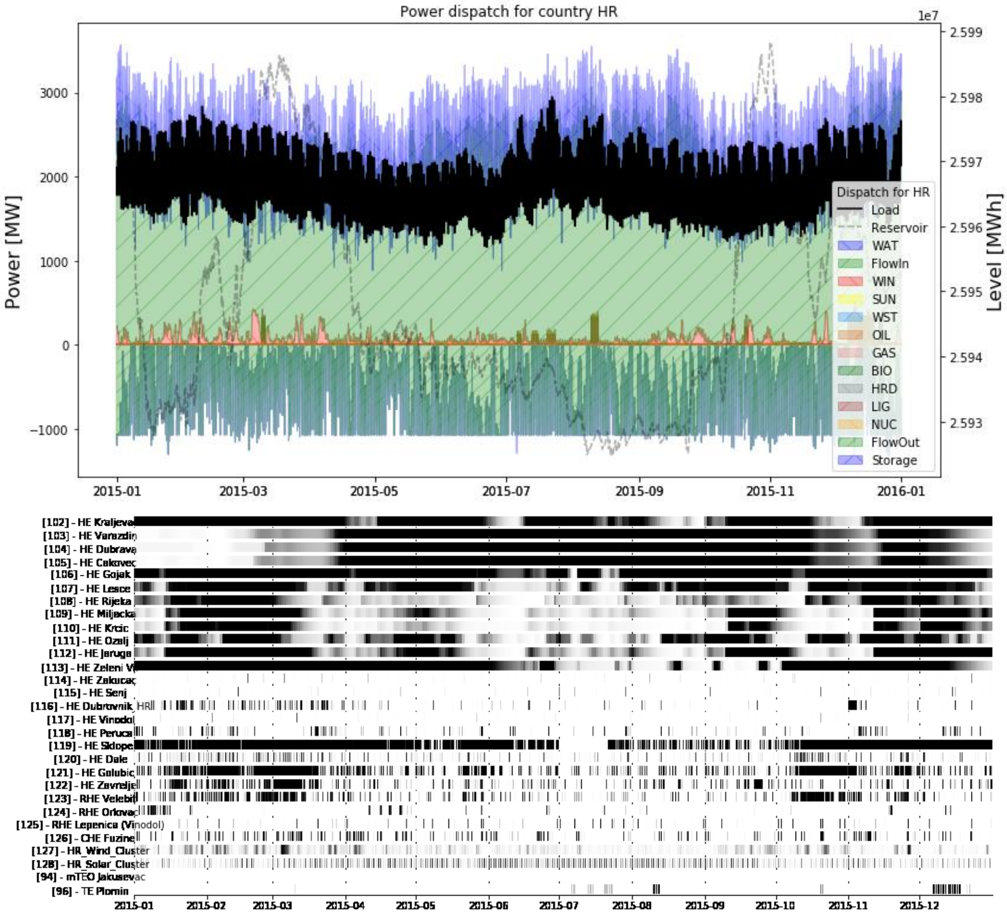
[114] - HE Senj
[115] - HE Dubrovnik_HR
[116] - HE Vinodol
[117] - HE Peruca
[118] - HE Sklope
[119] - HE Dale
[120] - HE Golubic
[121] - HE Zavrelje
[122] - RHE Velebit
[123] - RHE Orlovac
[124] - RHE Lepenica (Vinodol)
[125] - CHE Fuzine
[126] - HR_Wind_Cluster
[127] - HR_Solar_Cluster
[92] - KTE Jertovec
[93] - mTEO Jakusevac
[95] - TE Plomin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Power [MW]
Level [MWh]
1e7
Dispatch for HR
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
2015-01
2015-03
2015-05
2015-07
2015-09
2015-11
2016-01
[102] - HE Kraljevac
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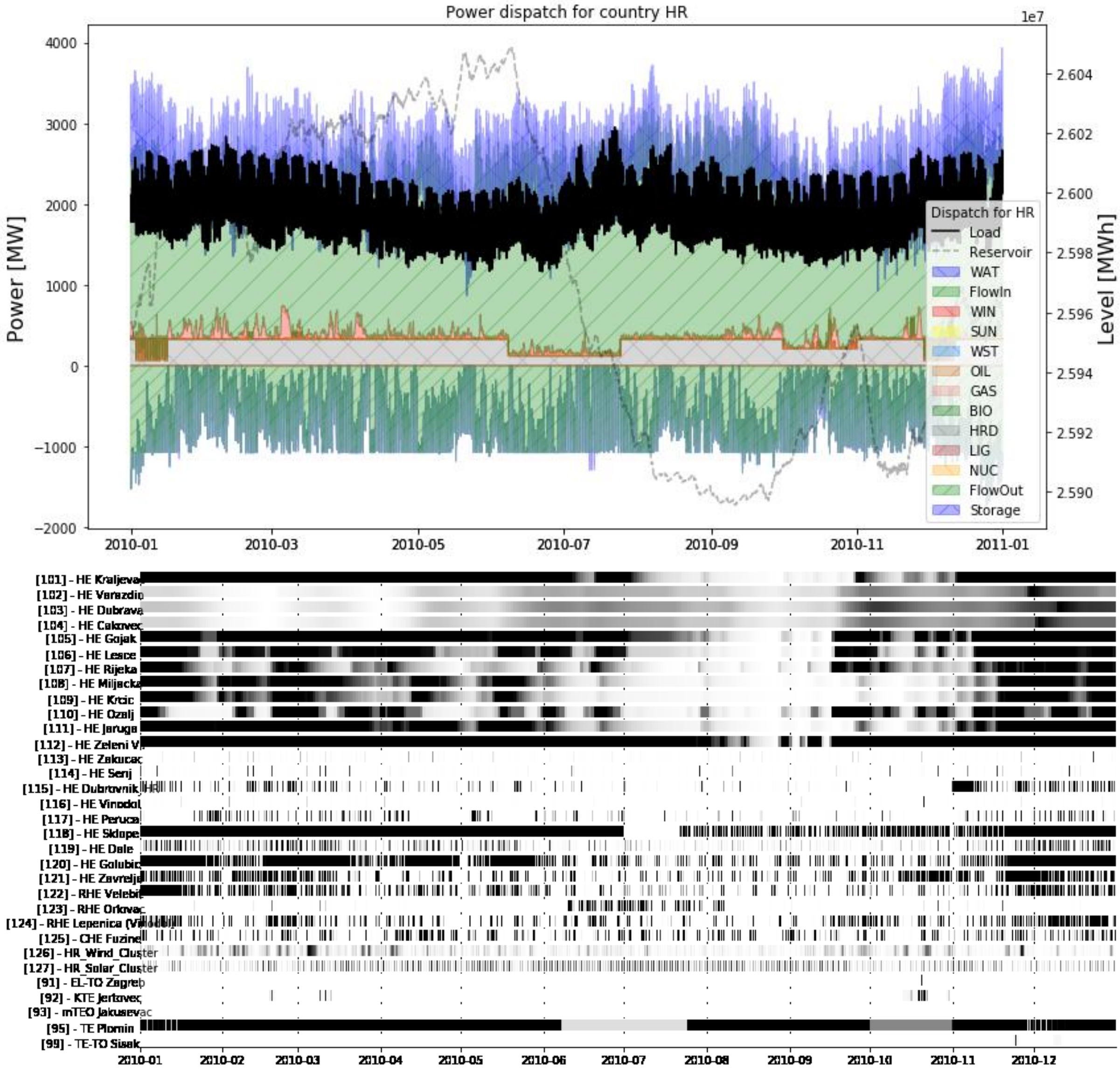
Power dispatch for country HR
1e7
Power [MW]
Level [MWh]
4000
3000
2000
1000
0
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−2000
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2.594
2.592
2.590
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2010-11
2011-01
Dispatch for HR
Load
Reservoir
WAT
FlowIn
WIN
SUN
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HRD
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NUC
FlowOut
Storage
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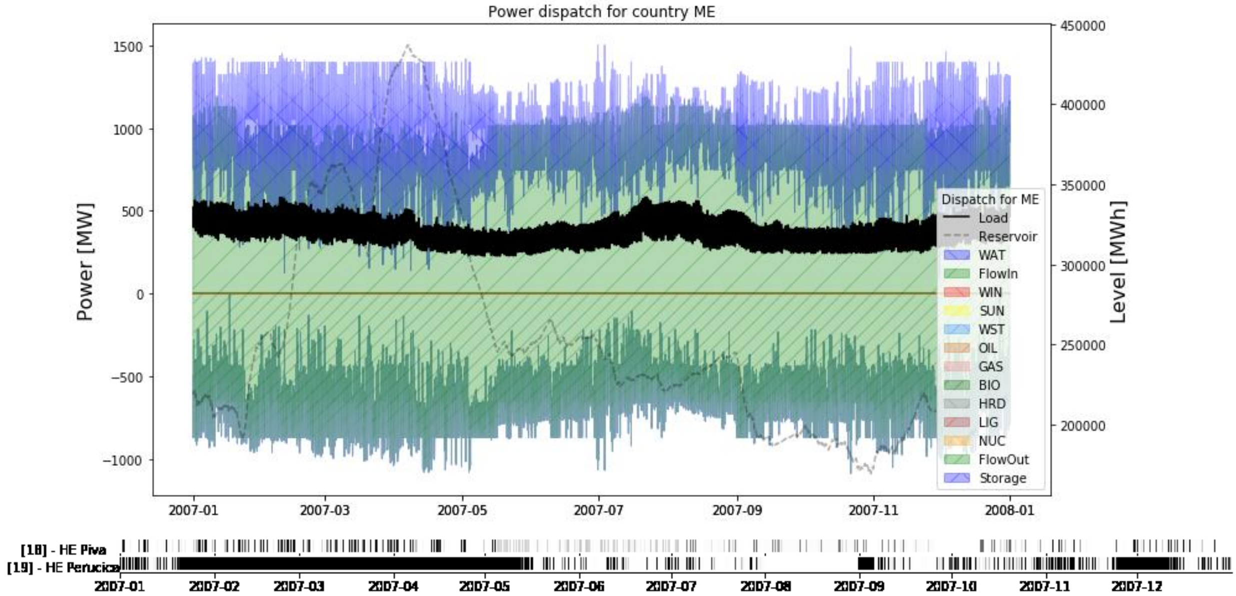
2010-12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Power [MW]
Level [MWh]
Dispatch for ME
Load
Reservoir
WAT
FlowIn
WIN
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HRD
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NUC
FlowOut
Storage
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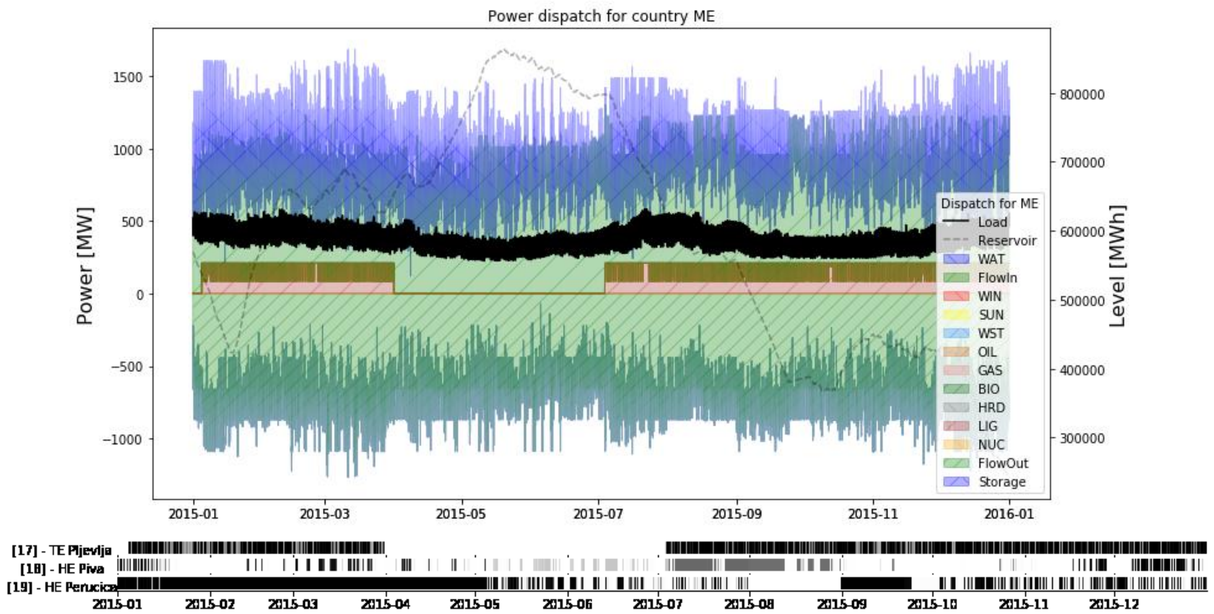
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Power [MW]
Level [MWh]
Dispatch for ME
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FlowIn
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LIG
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FlowOut
Storage
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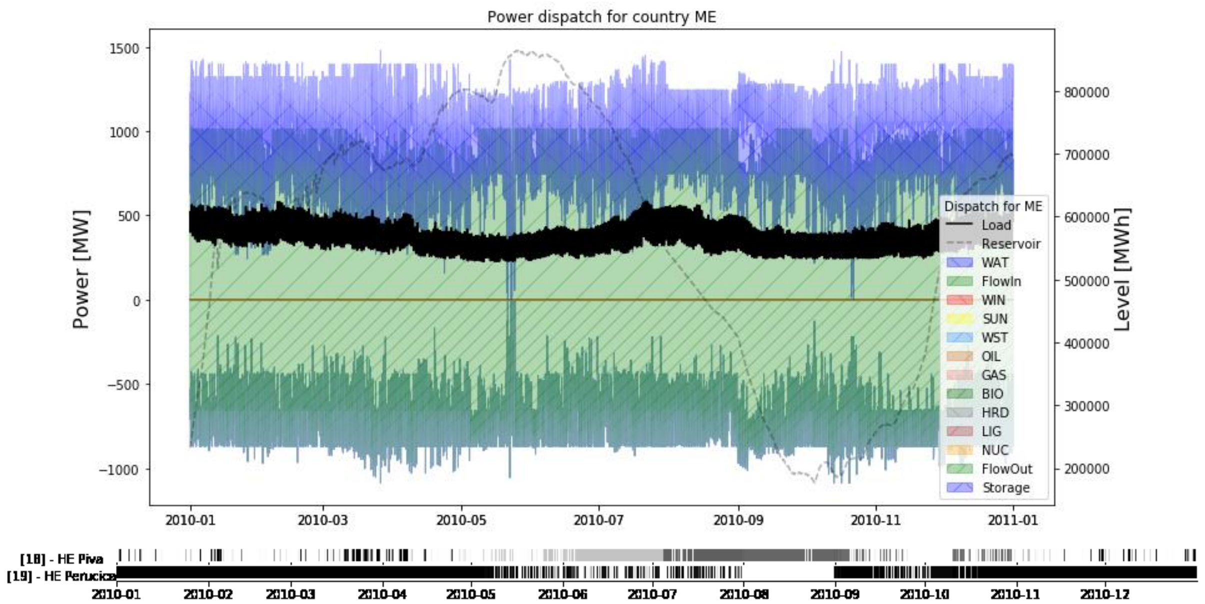
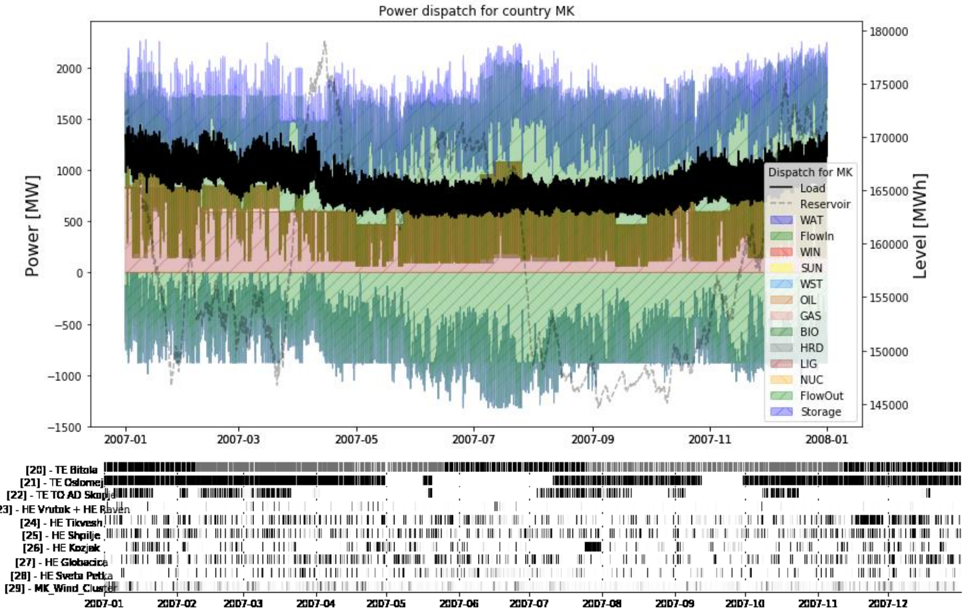
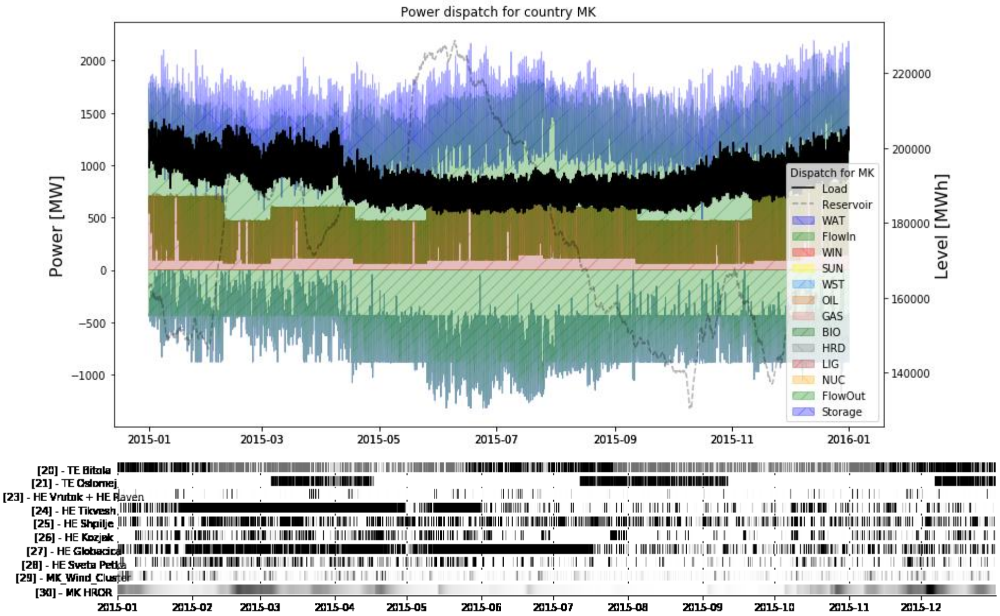
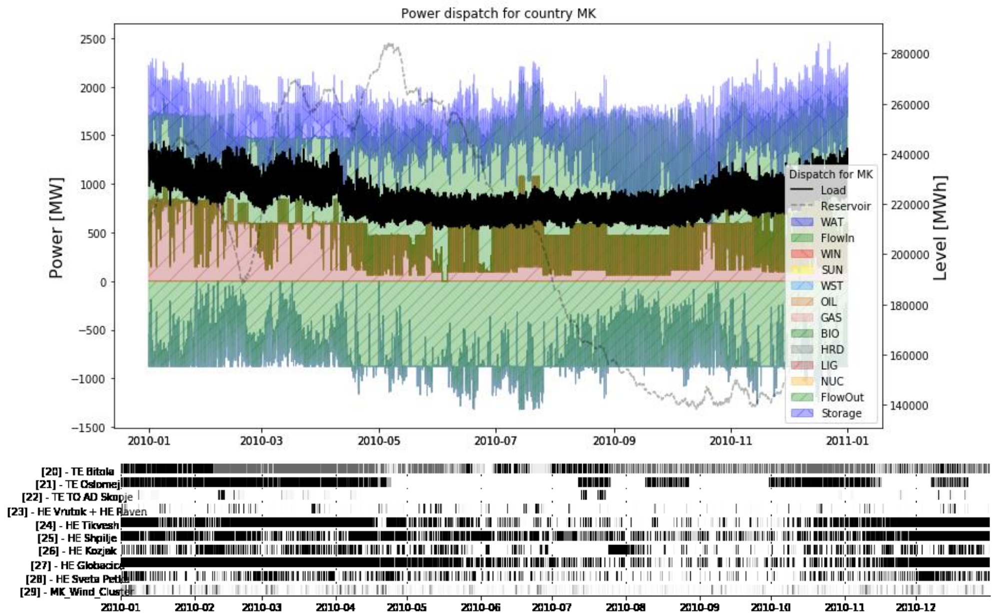
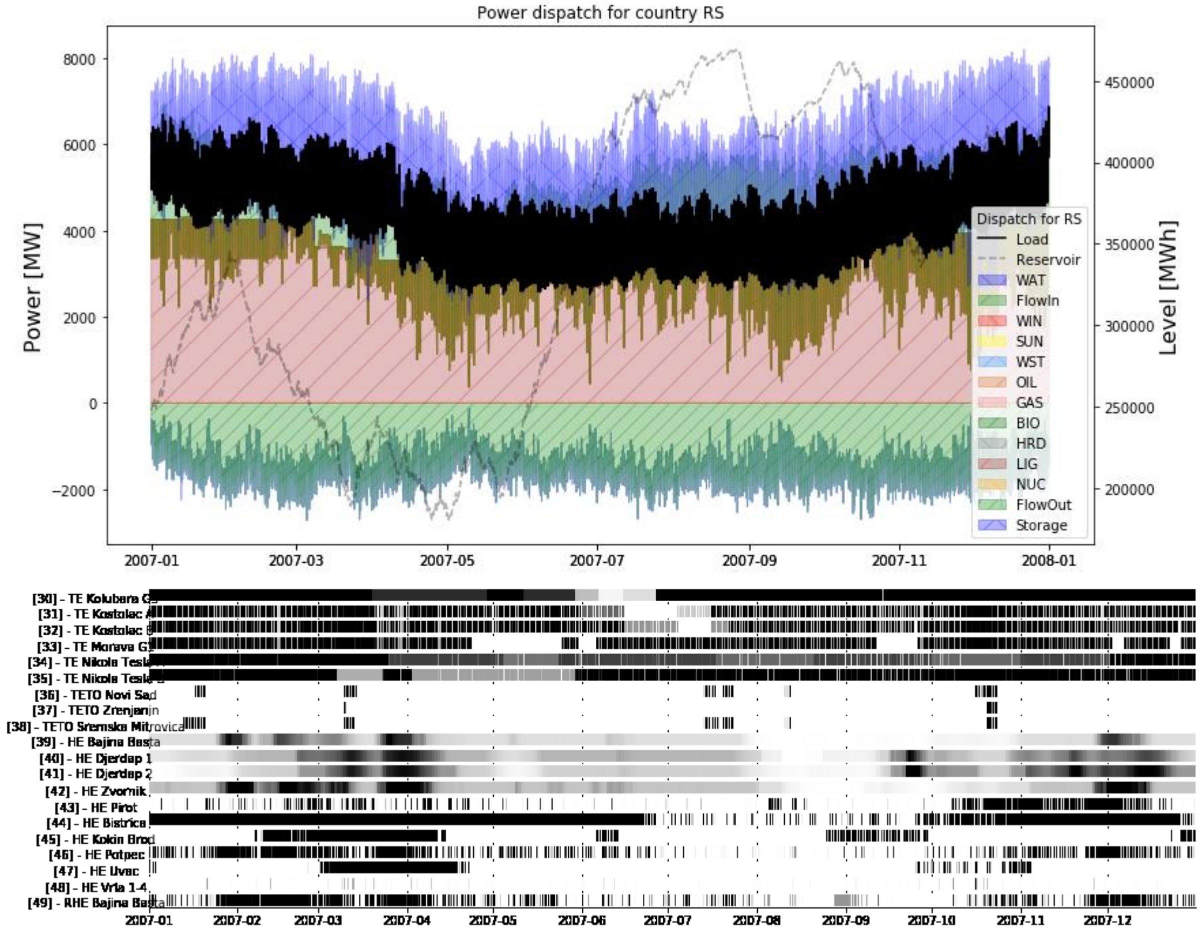
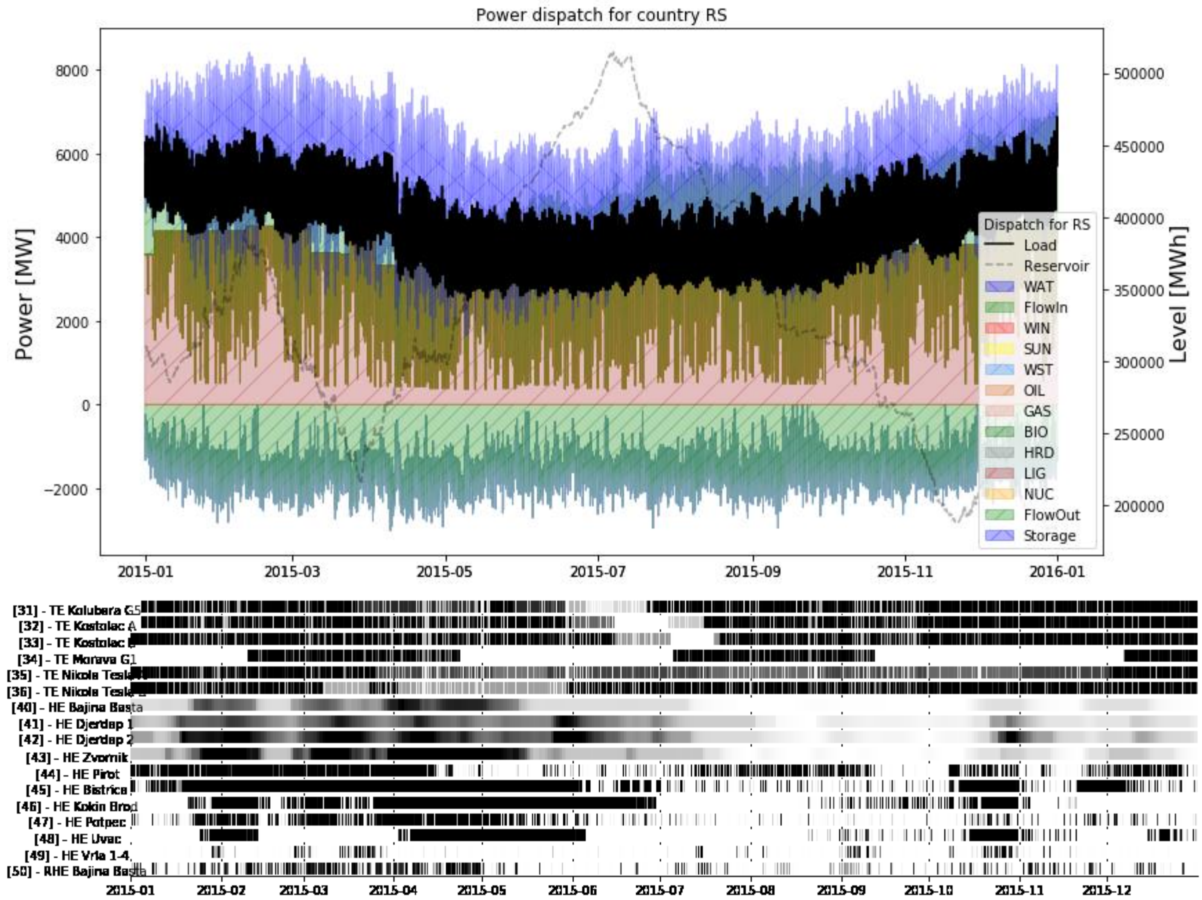

Power dispatch for country ME
Power [MW]
Level [MWh]
Dispatch for ME
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[18] - HE Piva
[19] - HE Perucica

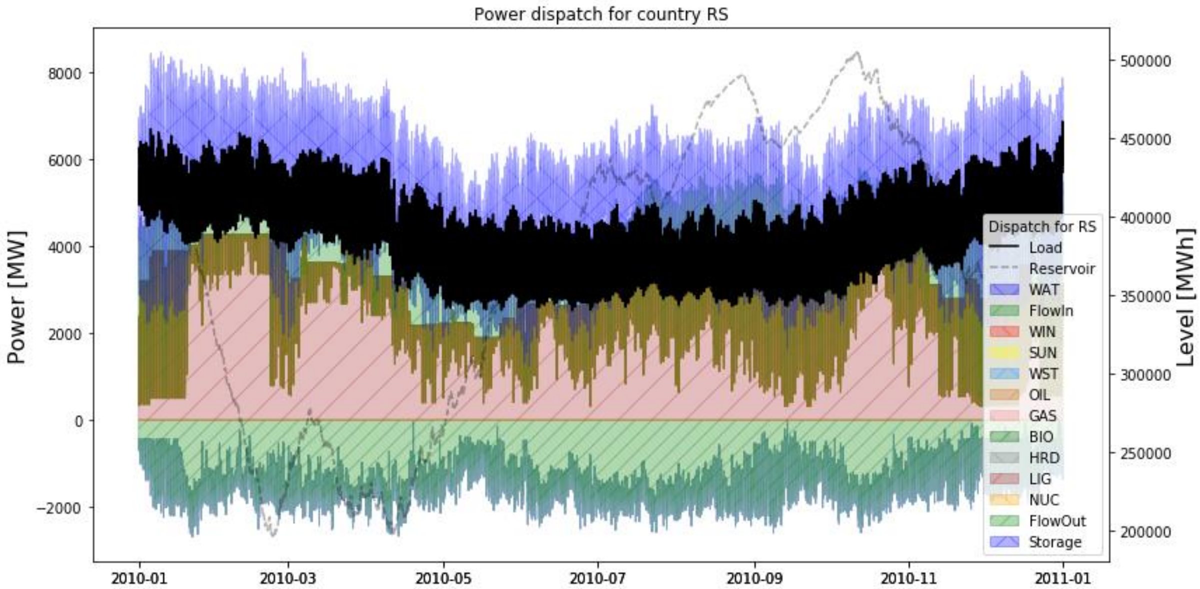

Power dispatch for country MK
Power [MW]
Level [MWh]
Dispatch for MK
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[20] - TE Bitola
[21] - TE Oslomej
[22] - TE TO AD Skopje
[23] - HE Vrutok + HE Raven
[24] - HE Tikvesh
[25] - HE Shpilje
[26] - HE Kozjak
[27] - HE Globacica
[28] - HE Sveta Petka
[29] - MK_Wind_Cluster

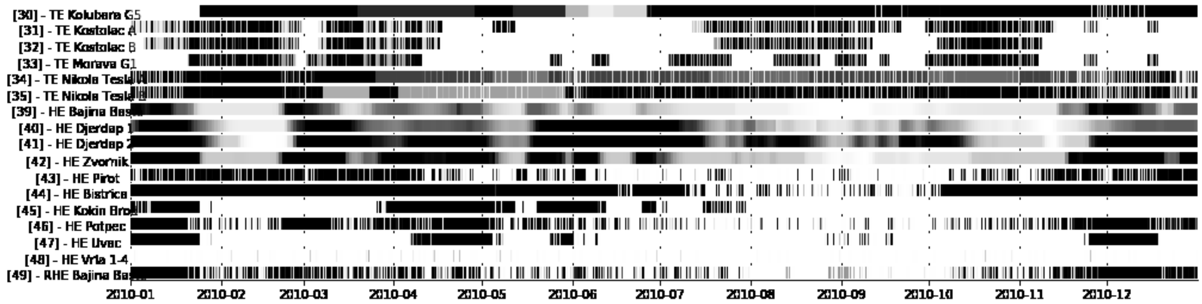

Power dispatch for country MK
Power [MW]
Level [MWh]
Dispatch for MK
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[20] - TE Bitola
[21] - TE Oslomej
[23] - HE Vrutok + HE Raven
[24] - HE Tikvesh
[25] - HE Shpilje
[26] - HE Kozjak
[27] - HE Globacica
[28] - HE Sveta Petka
[29] - MK_Wind_Cluster
[30] - MK HROR

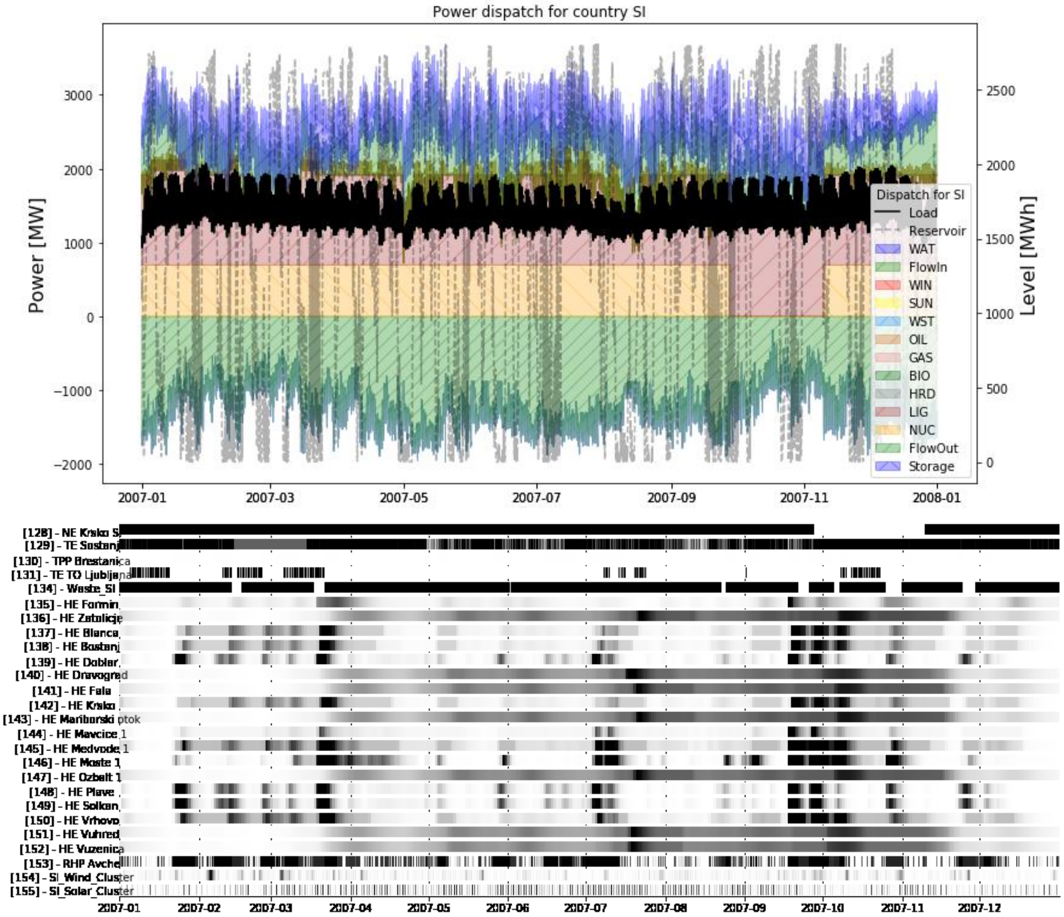

Power dispatch for country MK
Power [MW]
Level [MWh]
Dispatch for MK
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[20] - TE Bitola
[21] - TE Oslomej
[22] - TE TO AD Skopje
[23] - HE Vrutok + HE Raven
[24] - HE Tikvesh
[25] - HE Shpilje
[26] - HE Kozjak
[27] - HE Globacica
[28] - HE Sveta Petka
[29] - MK_Wind_Cluster

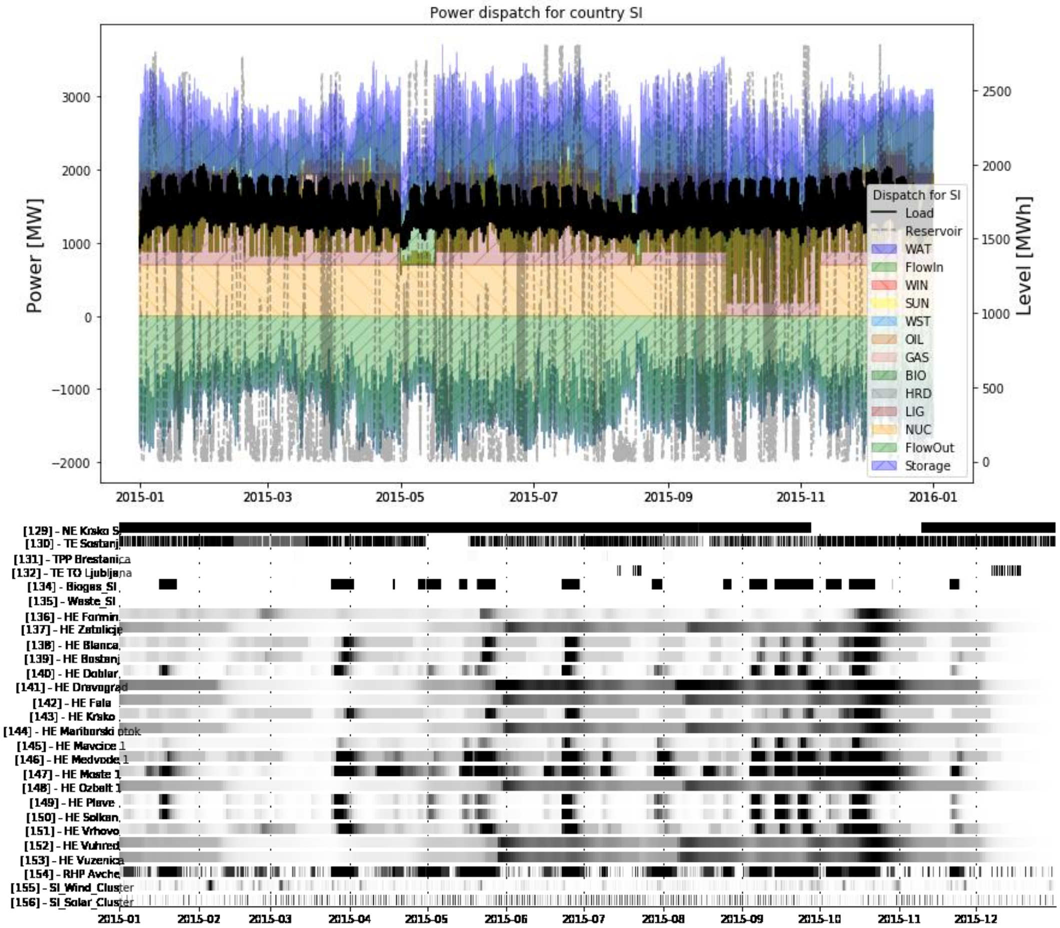

Power dispatch for country RS
Power [MW]
Level [MWh]
Dispatch for RS
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
2007-01
2007-03
2007-05
2007-07
2007-09
2007-11
2008-01
[30] - TE Kolubara G5
[31] - TE Kostolac A
[32] - TE Kostolac B
[33] - TE Morava G1
[34] - TE Nikola Tesla A
[35] - TE Nikola Tesla B
[36] - TETO Novi Sad
[37] - TETO Zrenjanin
[38] - TETO Sremska Mitrovica
[39] - HE Bajina Basta
[40] - HE Djerdap 1
[41] - HE Djerdap 2
[42] - HE Zvornik
[43] - HE Pirot
[44] - HE Bistrica
[45] - HE Kokin Brod
[46] - HE Potpec
[47] - HE Uvac
[48] - HE Vrla 1-4
[49] - RHE Bajina Basta

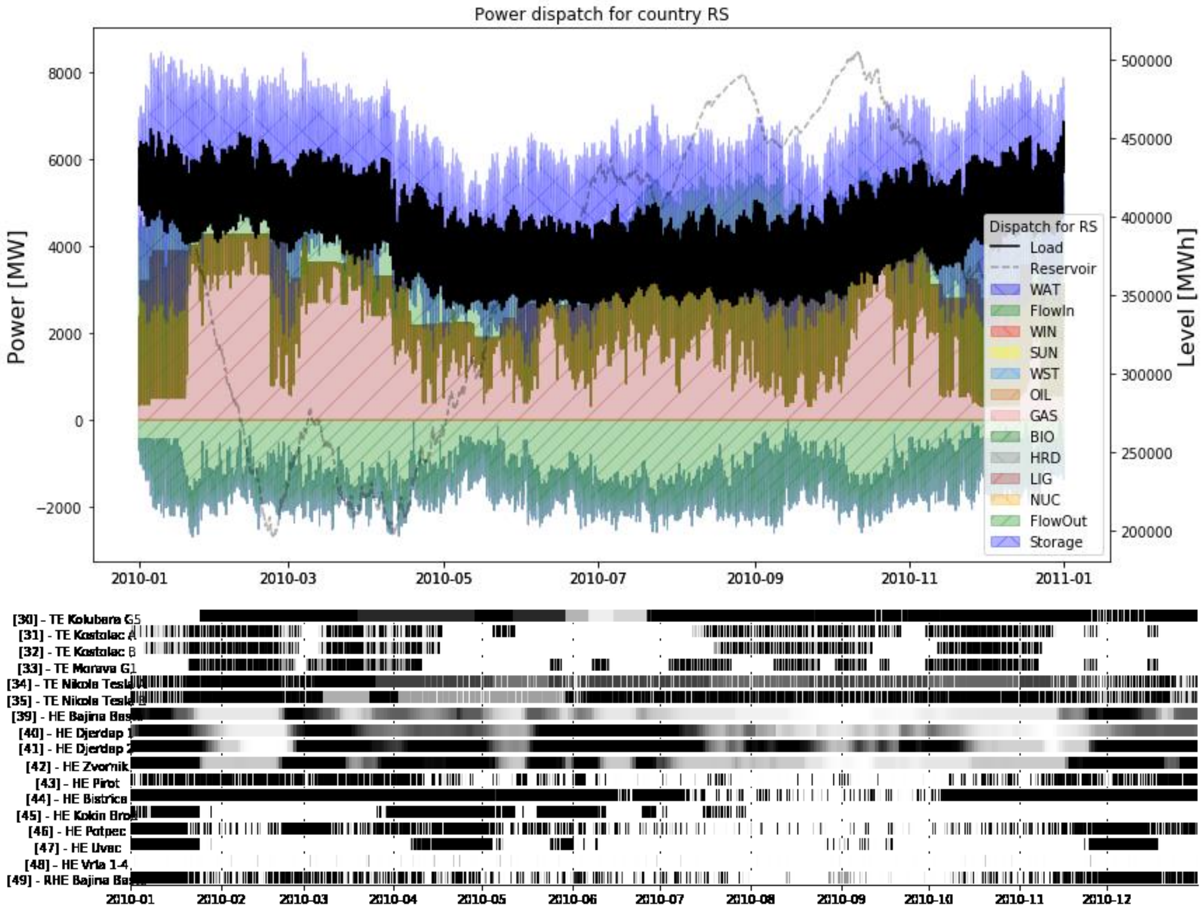

Power dispatch for country RS
Power [MW]
Level [MWh]
Dispatch for RS
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
2015-01
2015-03
2015-05
2015-07
2015-09
2015-11
2016-01
[31] - TE Kolubara G5
[32] - TE Kostolac A
[33] - TE Kostolac B
[34] - TE Morava G1
[35] - TE Nikola Tesla A
[36] - TE Nikola Tesla B
[40] - HE Bajina Basta
[41] - HE Djerdap 1
[42] - HE Djerdap 2
[43] - HE Zvornik
[44] - HE Pirot
[45] - HE Bistrica
[46] - HE Kokin Brod
[47] - HE Potpec
[48] - HE Uvac
[49] - HE Vrla 1-4
[50] - RHE Bajina Basta

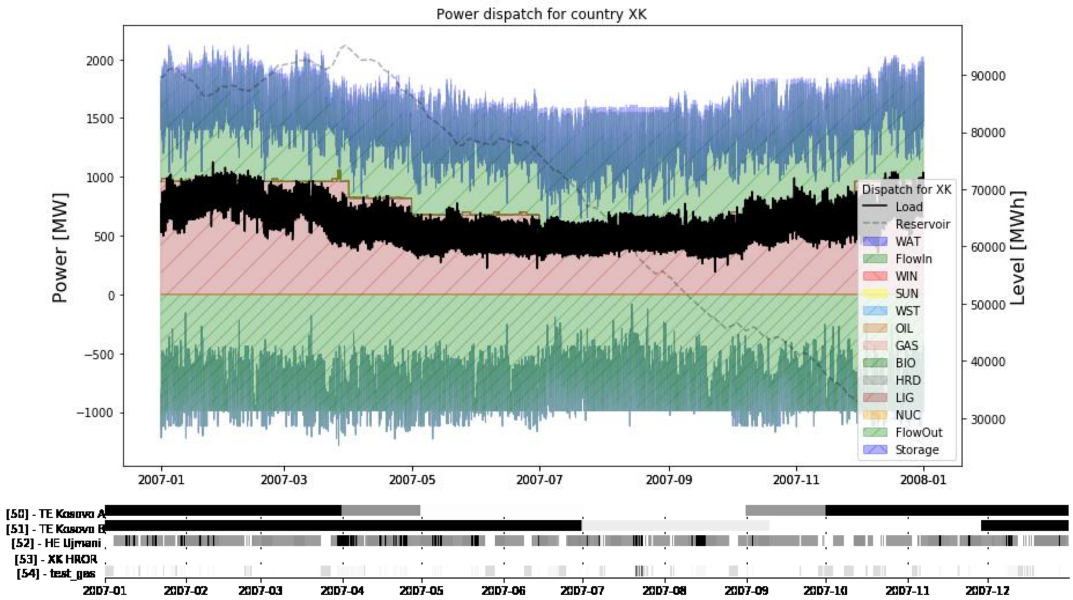

Power dispatch for country RS
Power [MW]
Level [MWh]
8000
6000
4000
2000
0
−2000
500000
450000
400000
350000
300000
250000
200000
2010-01
2010-03
2010-05
2010-07
2010-09
2010-11
2011-01
Dispatch for RS
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage

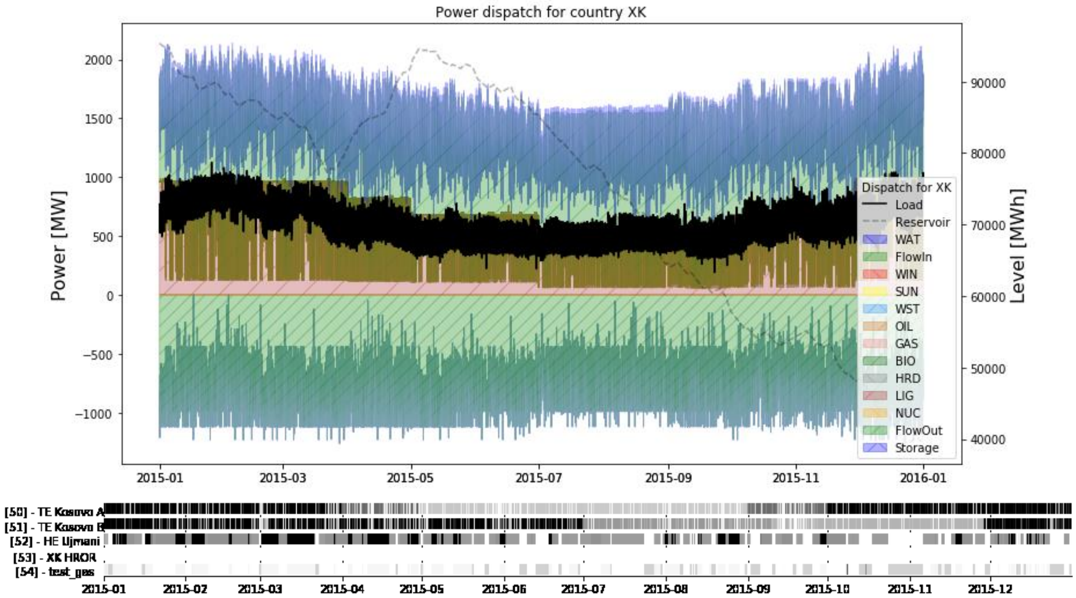

[30] - TE Kolubara G5
[31] - TE Kostolac A
[32] - TE Kostolac B
[33] - TE Morava G1
[34] - TE Nikola Tesla
[35] - TE Nikola Tesla
[39] - HE Bajina Bas
[40] - HE Djerdap 1
[41] - HE Djerdap 2
[42] - HE Zvornik
[43] - HE Pirot
[44] - HE Bistrica
[45] - HE Kokin Brod
[46] - HE Potpec
[47] - HE Uvac
[48] - HE Vrla 1-4
[49] - RHE Bajina Bas
2010-01
2010-02
2010-03
2010-04
2010-05
2010-06
2010-07
2010-08
2010-09
2010-10
2010-11
2010-12

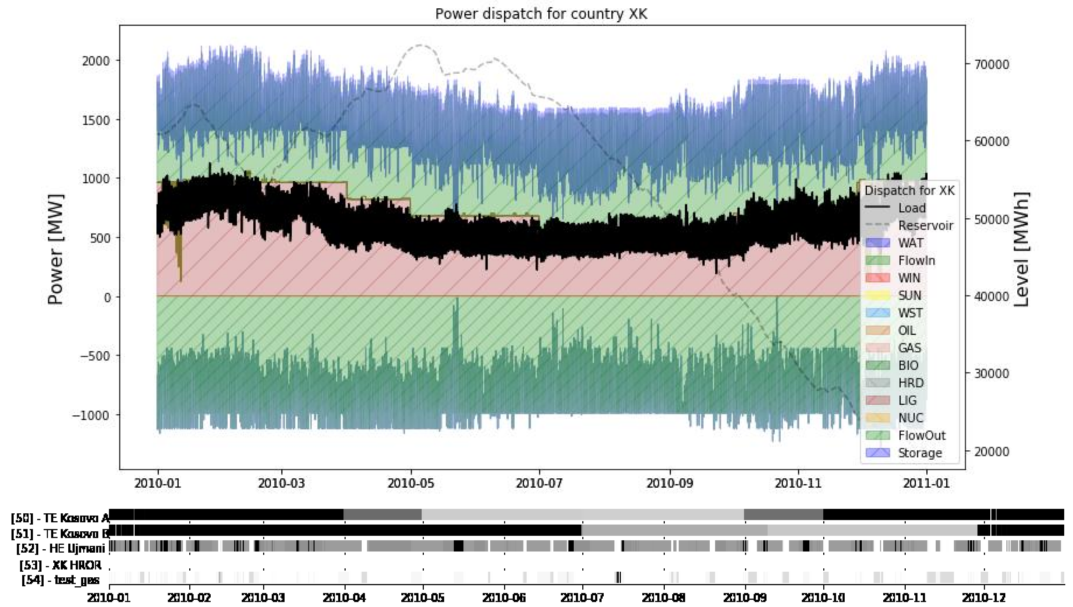

Power dispatch for country SI
Power [MW]
Level [MWh]
Dispatch for SI
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage


Power dispatch for country SI
Power [MW]
Level [MWh]
Dispatch for SI
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage


Power dispatch for country RS
Power [MW]
Level [MWh]
Dispatch for RS
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[30] - TE Kolubara G5
[31] - TE Kostolac A
[32] - TE Kostolac B
[33] - TE Morava G1
[43] - HE Pirot
[44] - HE Bistrica
[46] - HE Potpec
[47] - HE Uvac
[48] - HE Vrla 1-4


Power dispatch for country XK
Power [MW]
Level [MWh]
Dispatch for XK
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[50] - TE Kosovo A
[51] - TE Kosovo B
[52] - HE Ujmani
[53] - XK HROR
[54] - test_gas


Power dispatch for country XK
Power [MW]
Level [MWh]
Dispatch for XK
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[50] - TE Kosovo A
[51] - TE Kosovo B
[52] - HE Ujmani
[53] - XK HROR
[54] - test_gas


Power dispatch for country XK
Power [MW]
Level [MWh]
Dispatch for XK
Load
Reservoir
WAT
FlowIn
WIN
SUN
WST
OIL
GAS
BIO
HRD
LIG
NUC
FlowOut
Storage
[50] - TE Kosovo A
[51] - TE Kosovo B
[52] - HE Ujmani
[53] - XK HROR
[54] - test_gas