Primjena modela DispaSET na elektroenergetski sustav zemalja Zapadnog Balkana

Tomić, Ivan

UNIVERSITY OF ZAGREB FACULTY OF MECHANICAL
ENGINEERING AND NAVAL ARCHITECTURE

MASTER'S THESIS

Ivan Tomić

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UNIVERSITY OF ZAGREB FACULTY OF MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE

Applying the DispaSET model on the Western Balkans power systems

Mentor:

Prof. dr. sc. Neven Duić, dipl. Ing.

Student:

Ivan Tomić

Zagreb, godina 2017.

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I hereby declare that this thesis is eniterely the result of my own work except where otherwise indicate. I have fully cited all used sources and I have only used the one given in the list of references.

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Datum	Prilog
Klasa:	
Ur.broj:	

DIPLOMSKI ZADATAK

Student: **Ivan Tomić** Mat. br.: 0035187616

Naslov rada na hrvatskom jeziku: **Primjena DispaSET modela na elektroenergetski sustav Zapadnog Balkana**

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Opis zadatka:

Worldwide demand for energy is continuously increasing. At the same time, renewable energy sources such as wind, solar and biofuels are becoming more competitive and available due to technological advancements, access to an open market and a shift in EU (European Union) directives and national legislations. In order to slow down the ongoing climate change, increase the security of energy supply and ensure competitive energy prices in the region, the EU has adopted the 2020 climate & energy action plan. The key targets of this plan focus on the reduction of GHG (greenhouse gas emissions) by 20% compared to 1990 levels, increase the share of renewable energy sources in the EU energy mix to 20% and increase of energy efficiency by 20% till the year 2020. The 2030 Energy strategy has set even more ambitious goals with a planned cut in GHG emissions of 40%, a share of renewable energy consumption of at least 27% and at least 27% energy savings compared to a business-as-usual scenario. In order to tackle the set targets in future scenarios policy makers need to consider issues such as the effects of intermittent energy sources, identify potential of energy storage and amount of backup capacity required to safely meet the demand.

In the thesis it is necessary to complete the tasks outlined below:

a) A detailed review of the stochastic nature of historic fuel prices and climate data, including national power systems in Western Balkan countries will be completed
b) Power plant data of all available units will be analysed and imported into the model. Time series related to the fuel prices, scheduled plant outages, weather data, hydrology of rivers, cross border energy flows and storage levels will be either downloaded or modelled and imported into the model.
c) An energy system analysis will be carried out using the DispaSET model. Its verification will be carried out on the Western Balkan power systems. This will be done for a chosen reference year. In addition to this, additional scenarios will be developed to analyse how future 2020 and 2030 EU climate and action plans will impact the current power systems, especially through integration of locally available renewable energy sources such as wind, solar and geothermal energy and biofuels.

Necessary data and literature could be obtained from the supervisors. In the thesis, it is also necessary to state used literature and received help.

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NOMENCLATURE

Symbol	Unit	Description
$P_{tr,h}$	MW	is power output of unit powered by renewable energy sources tr in each time interval h
$P_{max_{tr}}$	MW	is maximal power of unit powered by renewable energy sources tr
$Q_{tr,h}$	MWh	is river discharge of unit powered by renewable energy sources tr in each time interval h
Q_{max_u}	MWh	is maximal river discharge of unit powered by renewable energy sources tr
$P_{u,h}$	MW	is power output of unit u in each time interval h
$I_{l,h}$	MW	is sum of hourly imports between a specific country and the rest of the world
$E_{l,h}$	MW	is sum of hourly imports between a specific country and RoW
$Dem_{electricity_h}$	MW	s hourly electricity demand of a country in each time interval h
NTC_l	MW	is net transfer capacity of transmission line l
$E_{s,h}$	MWh	is energy stored in accumulation unit s in each time interval h
E_{max_s}	MWh	is maximal energy stored in accumulation of storage unit s
$E_{initial,s}$	MWh	is initial energy stored in accumulation unit s
$Dem_{HDAM_{s,h}}$	MW	s electricity demand of storage unit s in each time interval h
$Inflow_{s,h}$	MWh/h	is inflow of storage unit s in each time interval h
η_{HDAM}	-	is efficiency of accumulation hydro power plant
ρ	kg/m^3	is density
g	m/s^2	is gravity constant
h_{max_s}	m	is maximal head of storage unit s
Dem_{HDAM_h}	MW	is electricity demand of all storage units in each time interval h
E_{prod_s}	MWh	is energy produced by storage unit s in one year
P_{max_s}	MW	is maximal power of storage unit s
Q_{max_s}	MWh	s maximal flow of storage unit s

$P_{HROR_{u,h}}$	MW	is hourly power output of run-of-river hydro unit in each time interval h
P_{TPP_h}	MW	is power output of all thermal power plants including steam turbine, gas turbine and combined cycle in each time interval h
C_{STUR}	MWh	is correction factor for thermal power plants that has been determined iteratively
Dem_{TPP_h}	MWh	s electricity demand of all thermal power plants in each time interval h
$P_{min_{h,u}}$	MW	is hourly power output of thermal power plant with smallest installed power
P_{max_u}	MW	is maximal power of unit u

Units

MWh	Kilowatt hour	Energy
GWh	Megawatt hour	Energy
TWh	Terawatt hour	Energy
MW	Megawatt	Capacity
kg	Kilogram	Mass
t	Tonne	Mass
m^2	Square meter	Area
m^3	Cubic metre	Volume

Abbreviations

AF	Availability factor
CHP	Combined Heat and Power Plant
CO_2	Carbon dioxide
EU	European union
GHG	Greenhouse Gas
OF	Outage factor
RES	Renewable energy source
RL	Reservoir level
RoW	Rest of the World
SI	Scaled inflows

Economy

EUR	Euro
€	Euro

ABSTRACT

This thesis describes implementation of the DispaSET model on the Western Balkans power system. The goal is to demonstrate the power sector of four Western Balkan countries, Bosnia and Herzegovina, Kosovo, Montenegro and Serbia in order to accelerate the development and deployment of cost-effective low carbon technologies.

With increased energy planning needs and new regulations, environmental agencies, state energy offices and others have expressed more of an interest in electric power sector models.

The first step for creating the proper model was to gather all the available data relevant for describing power system of each country. Afterwards, methods of data processing are displayed in order to be compatible with model. The methods were generalised and being used for every country.

Secondly, all the input data are described for all four countries, and the simulation process has been carried out simultaneously for the whole region.

Three scenarios have been developed. One reference scenario and two alternatives. For the reference scenario the year 2010 has been chosen due to the data availability. Alternative scenarios are made for the year 2020 and 2030. Each of alternative scenarios has three cases, A, B and C. Cases A and B are developed according to the national reports of each country. These two case are identical and the only difference is that the Case B works in the island regime. The Case C is a strategy with high penetration of renewable energy sources in to the power sector.

Results from the reference year scenario have been validated as they accurately represent the data from the real world. Main indicator for validation of the additional scenarios was average price of electricity calculated by the model.

KEY WORDS: DispaSET, Energy planning, The Western Balkans

SAŽETAK

U ovome radu prikazana je implementacija DispaSET modela na zemlje Zapadnoga balkana. Glavni cilj je prikazati energetski sektor zemalja Zapadnog Balkana, Crne Gore, Bosne i Hercegovine, Kosova i Srbije kako bi se ubrzao razvoj i integracija obnovljivih izvora energije te kako bi se ispitala održivost energetskih strategija svake pojedine zemlje.

Povećanjem potrebe za energetskim planiranjem i novim regulacijskim okvirima, energetske agencije i vladine organizacije iskazuju potrebu za stvaranjem modela koji bi simulirao ponašanje energetskog sustava.

Prvi korak u stvaranju modela je prikupljanje podataka koji opisuju energetski sektor svake od promatranih država. Zatim je prikazana metodologija kojom su se prikupljeni podaci prilagođavali ulaznom modelu. Svaka od metoda je generalizirana i primijenjena na sve države.

U nastavku rada su opisani svi ulazni podaci za sve četiri zemlje, nakon čega je provedena simulacija energetskog sustava za svaku državu, te je promatrana na razini cijele regije. Simulacija je provedena za tri scenarija. Prvi scenarij predstavlja baznu godinu te je zbog dostupnosti podataka odabrana 2010. godina. Alternativni scenariji su modelirani za 2020. i 2030. godinu. Svaki od alternativnih scenarija ima tri zasebna slučaja, A, B i C. Slučajevi A i B su razvijeni prema strategijama nacionalnog razvoja svake države. Slučaj C je strategija sa visokim udjelom obnovljivih izvora energije u ukupno instaliranim kapacitetima.

U sklopu rezultata ispitana je točnost simulacije energetskog sektora za referentni scenarij. Točnost alternativnih scenarija je ispitana promatranjem prosječne cijene električne energije koju je odredio program.

KLJUČNE RIJEČI: DispaSET, Energetsko planiranje, Zapadni Balkan

PROŠIRENI SAŽETAK (EXTENDED SUMMARY IN CROATIAN)

U uvodnom poglavlju opisana je problematika svjetskog i europskog energetskog sustava.. Unatoč velikom naporu da se smanji korištenje fosilnih goriva, ugljen, nafta i prirodni plin bilježe porast u udjelu proizvodnje električne energije. Europska Unija je usvojila akcijski plan koji za cilj ima smanjenje stakleničkih plinova za 20% i povećanje energetske učinkovitosti za 20% do 2020. godine. Kako bi se ostvarili zadani ciljevi, potrebni su novi izvori energije koji imaju mali utjecaj na okoliš. Obnovljivi izvori energije imaju važnu ulogu u ostvarivanju tih ciljeva, te njihova primjena u energetskom sustavu rezultira mnogim prednostima. Najvažnija je smanjenje emisija stakleničkih plinova, prvenstveno zbog toga što obnovljivi izvori energije ne proizvode štetne emisije prilikom proizvodnje električne energije. Prednosti su također i povećanje energetske sigurnosti i neovisnosti te sigurnosti dobave.

Prilikom analize energetskog sustava zemalja Zapadnog Balkana zaključeno je sljedeće: Dominantnu ulogu u proizvodnji električne energije imaju termoelektrane na lignit i hidroelektrane, dok je udio obnovljivih izvora zanemariv. Svaka država unutar Zapadnog Balkana ima rudnike lignita i ugljenokope unutar kojih se ruda iskapa i transportira do svake termoelektrane. Većina rudnika su, kao i elektrane, u nacionalnom vlasništvu koje različitim iznosima subvencija potpomažu njegovu proizvodnju. Iz tog razloga je teško pronaći stvarnu cijenu lignita.

Povećanjem potrebe za energetskim planiranjem i novim regulacijskim okvirima, energetske agencije i vladine organizacije iskazuju potrebu za stvaranjem modela koji bi simulirao ponašanje energetskog sustava. Primjena takvih modela je bitna u pogledu procjene budućih zahtijeva za električnom energijom i određivanja na koji bi se način vršila opskrba električnom energijom. Opskrba električne energije se može ostvariti na različite načine i iz različitih izvora energije.

Danas su dostupni brojni programi koji simuliraju ponašanje energetskog sustava. Računalni program korišten u ovome radu je DispaSET. On simulira energetski sustav na satnoj razini te u svakom trenutku određuje raspored paljenja i gašenja svake elektrane na način da ukupni troškovi proizvodnje električne energije budu minimalni.

Glavni cilj ovoga rada je prikazati energetski sektor zemalja Zapadnog Balkana, Crne Gore, Bosne i Hercegovine, Kosova i Srbije kako bi se ubrzao razvoj i integracija obnovljivih izvora energije te kako bi se ispitala održivost energetskih strategija svake pojedine zemlje.

Prvi korak u stvaranju modela je prikupljanje podataka koji opisuju energetski sektor svake od promatranih država., uključujući tehničke parametre svih elektrana, povijesno kretanje cijena energenata, planirane i neplanirane remonte, hidrologiju rijeka, vremenske podatke, međugraničnu razmjenu, tokove električne energije te razine akumulacija svih dostupnih elektrana sa mogućnošću pohrane električne energije.

Nako toga je prikazana metodologija kojom su se prikupljeni podaci prilagođavali ulaznom modelu. Metodologija obuhvaća različite jednadžbe pomoću kojih su obrađivani podaci u svrhu kreiranja parametara za opisivanje modela energetskog sustava. Svaka od metoda je generalizirana i primijenjena na sve države koristeći Microsoft Excell kao pomoćni program.

U nastavku rada su opisani svi ulazni podaci i navedene su optimizacijske varijable koje računalni alat koristi za simuliranje energetskog sektora. Ulazni podaci su opisani kao satne vrijednosti na godišnjoj razini. Lista ulaznih podataka je:

- Tehnički podaci svih postrojenja za proizvodnju električne energije (eng. *Power plants*)
- Faktor dostupnosti (eng. *Availability factor*) za postrojenja na obnovljive izvore energije
- Skalirani protoci rijeka (eng. *Scaled inflows*) koji se koriste za hidroelektrane
- Razine akumulacija (eng. *Reservoir level*) hidroelektrana
- Faktor dostupnosti (eng. *Outage Factor*)
- Vrijednosti transmisijskih kapaciteta (eng. *Net transfer capacities*) između susjednih država
- Tokovi električne energije između susjednih država (eng. *Cross border flows*)
- Cijene goriva (eng. *Fuel prices*)
- Satno električno opterećenje (eng. *Load real-time*)

Svi ranije navedeni podaci su detaljno opisani za sve četiri zemlje. Za svaku su zemlju predstavljeni i općeniti podaci kao što su ime glavnog grada, populacija u 2010. godini, popis država s kojima graniči kao i iznos transmisijskih kapaciteta između susjednih država. Cijene goriva, vrijednosti transmisijskih kapaciteta i tokovi električne energije između susjednih država su izdvojeni i opisani kao zajednički svim zemljama.

Nakon određenih ulaznih parametara, provedena je simulacija energetskog sustava za svaku državu, te je promatrana na razini cijele regije. Simulacija je provedena za tri scenarija. Prvi scenarij predstavlja baznu godinu te je zbog dostupnosti podataka odabrana 2010. godina. Alternativni scenariji su modelirani za 2020. i 2030. godinu. Svaki od alternativnih scenarija ima tri zasebna slučaja, A, B i C. Slučajevi A i B su razvijeni na prema strategijama nacionalnog razvoja svake države. Oba slučaja imaju iste ulazne podatke a razlika je u tome što Slučaj B radi u otočnom radu, što znači da nema razmjene električne energije sa susjednim državama Zapadnog Balkana, nego se razmjena odvija samo unutar promatrane regije. Slučaj B je zanimljiv

zbog toga što opisuje održivost razvoja prema nacionalnim strategijama u pogledu energetske neovisnosti Zapadnog Balkana. Slučaj C je strategija sa visokim udjelom obnovljivih izvora energije u ukupno instaliranim kapacitetima. On je razvijen prema strategiji Europske Unije s ciljem da u 2020. godini ima 20% ukupno instaliranih kapaciteta iz obnovljivih izvora energije dok u 2030. godini taj cilj iznosi 30%. Slučaj C također radi u otočnom režimu. Glavni cilj modeliranja ranije navedenih scenarija je promatrati održivost strategija razvoja prema nacionalnim scenarijima i promatranje kako će se energetski sustavi ponašati u budućnosti. Također je zanimljivo za promatrati kako će se energetski sustav Zapadnog Balkana ponašati sa povećanim udjelom obnovljivih izvora energije u ukupno instaliranim kapacitetima.

U sklopu rezultata ispitana je točnost simulacije energetskog sektora za referentni scenarij. Referentni scenarij odabran je za povijesnu godinu pa su rezultati uspoređeni sa stvarnim podacima iz nacionalnih izvještaja svake zemlje. Usporedba se provodila na iznosima ukupno proizvedene električne energije pojedine države te cijele regije, te udjelima pojedine tehnologije u ukupno proizvedenoj električnoj energiji. Rezultati pokazuju odstupanja unutar unaprijed određenih granica te je model koji simulira energetski sustav Zapadnog Balkana u baznoj godini prihvaćen. Točnost alternativnih scenarija je ispitana promatranjem prosječne cijene električne energije koju je odredio program. Prosječna cijena električne energije pokazuje trend pada sa povećanim udjelima obnovljivih izvora energije, a razlog tomu leži u činjenici da su obnovljivim izvorima energije zadani niski operativni troškovi

Na kraju rada su dati glavni zaključci te je pokazano kako sve četiri promatrane zemlje mogu raditi u otočnom režimu, pri visokim udjelima obnovljivih izvora energije. Također su date smjernice i savjeti za buduća istraživanja.

1. INTRODUCTION

Worldwide demand for energy is continuously increasing. From 1971 till 2014, worlds total primary energy supply (TPES) has been multiplied by a factor of 2.5. Figure 1 shows how fossil fuels are still dominant in the total primary energy supply. The same is valid for the electricity production due to its abundance and low market price [1]. Combustion of fossil fuels and traditional uses of biomass for heating is a major source of local air pollution and a major contributor to a global GHG (greenhouse gas) emissions that are the main contributor to the global warming and increase of earth's atmosphere temperature. Despite numerous efforts related to the reduction of fossil fuel consumption in the electricity production Coal, Oil and Gas production is still rising due to its low costs in electrification of poor countries.

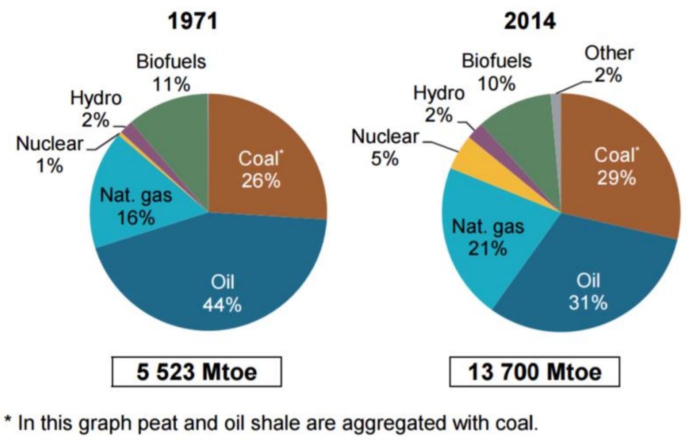

Figure 1 Total primary energy supply by fuel [1]

In order to slow down the ongoing climate change, increase the security of energy supply and ensure competitive energy prices in the region, EU has adopted 2020 climate & energy action plan which focuses on the reduction of GHG (greenhouse gas emissions) by 20% and increase of energy efficiency by 20% till the year 2020. Price of fossil fuels has been increasing over the past years, mostly because higher production costs, environmental risks and lower resource quality. This trend, of increasing fossil fuel costs, is about to rise even more in the next years when the carbon tax take in charge. At the same time, renewable energy resources such as wind, solar and biofuels are becoming more competitive and available due to technological advancements, access to an open market and shift in EU directives and national legislations. Renewable energy sources (RES) have major role in the reduction of GHG emissions. In most cases they minimize the impact on the environment as usually they do not emit GHG's during the electricity production. The Oil crisis that occurred in 1970 led to a greater interest in alternative and renewable energy sources. Higher share of RES in the power sector is utmost important for the security of energy supply. In future, RES will play key role in the reduction of GHG emissions, increasing energy security and slowing down global warming.

The region of Western Balkans, composed of Albania, Bosnia and Herzegovina, Croatia, the Former Yugoslav Republic of Macedonia, Montenegro, Serbia and Kosovo, is a complex region facing serious energy challenges. Literature suggest that conflicts over the break-up of the former Yugoslavia damaged much of the energy infrastructure and compounded the challenge of providing stabile energy supply. Furthermore, electricity systems in many parts of the region remain fragile and in need of investment because key elements of the energy infrastructure (e.g. major thermal power plants) were built in the 1960s and 1970s, with standard Eastern Block technology[2]. Literature also suggest that coal (mostly lignite) dominates the primary energy supply followed by oil, natural gas, hydropower and other renewables, mainly wind and solar. Apart from coal domination, hydropower and biomass already account for significant shares of the electricity mix and household heating needs. Moreover, The Western Balkan region is characterised by relatively high energy intensity levels that range up to 2.5 times higher than the average values observed in the European Union countries., and this can be attributed to three main factors: the degraded state of the energy infrastructure; high energy losses in transformation, transmission and distribution; and inefficiency in the end-use sector[2]. The whole region has high carbon intensity as a result of its heavy dependence on lignite [2][3] Every state within Western Balkans region has coal mines from where they produce and transfer lignite to thermal power plants. Most of these mines are, like power plants, owned by the government. It is in the interest of government that mines work at full capacity as much as they can because lot of local people work there. In order to ensure jobs for local population and boost the economy mines are being subsidised by government. Each country have its own direct and indirect subsidy and because of that it is difficult to establish lignite price. With increased energy planning needs and new regulations, environmental agencies, state energy offices and others have expressed more of an interest in electric power sector models. Implementation of such models is important for the planning of future demand and determination how that demand will be covered through energy policy development. Most energy planning models are used for scenario analysis that represents a coherent set of assumptions about possible future power systems.

There are lots of different software for simulation of electric power models and energy policy analysis. One of them is EnergyPLAN, which simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors[4]. It is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. Literature suggest that main purpose of the model is to assist the design of national and regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments, and the model is a deterministic input/output model. Furthermore general inputs are demands, renewable energy sources, energy station capacities, costs and a number of optional different regulation strategies emphasising import/export and excess electricity production. Outputs of the EnergyPLAN model are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity[4]. Another software tool for simulation of electric power system is LEAP. Literature describe LEAP as software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute and it is an integrated, scenario-based modelling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. Moreover, it can be used to account for both energy sector and non-energy sector GHG emission sources and sinks. LEAP is structured as a series of "views" of an energy system and the main "Analysis View" is the place where users create data structures and scenarios and enter all of the data describing both historical years and forward-looking scenarios.[5]

Energy planning tool that is being used in this work is DispaSET. The Dispa-SET model is a unit commitment and dispatch model developed within the JRC(Joint Research Centre) and focused on the balancing and flexibility problems in European grids[6]. It is written in Python and uses csv files for input data. The optimisation is defined as a LP (Linear Programming) or MILP (Mixed-Integer Linear Programming)) problem, depending on the desired level of accuracy and complexity[6].

DispaSET documentation describe that unit commitment problem consists of scheduling the start-up, operation, and shut down of the available generation units, as well as allocating the total power demand among the available generation units in such a way that the overall power system costs are minimized. Furthermore, the unit scheduling during certain periods of time, requires the use of binary variables in order to represent the start-up and shut down decisions, and the consideration of constraints linking the commitment status of the units in different periods while Economic dispatch problem determines the continuous output of each generation unit in the system[6][7]. Model has already been verified on Austria, Belgium, Switzerland, Germany, France and Netherland.

The goal of this work is to demonstrate the power sector of four Western Balkan countries, Bosnia and Herzegovina, Kosovo, Montenegro and Serbia in order to accelerate the development and deployment of cost-effective low carbon technologies.

2. METHODS

Following chapter coversmethods of data processing in order to be compatible with model. The methods were generalised and being used for every country.

This work covers many different types of technologies where each technology can potentially include a large number of units. In order to addres this issue a simplified index notation has been proposed where "u" stand for unit, "s" stand for storage unit, "l" stand for transmission line between countries and "tr" stand for renewable technologie.

2.1. River flows

River flows are series of data describing flow of each river in every hour. They are used for calculating power output, storage level and scaled inflows of hydro power plants.

River flows are modelled by two methods:

- obtained data from Riverwatch are daily values of river flow, and they are modify to hourly values using linear interpolation [8].
- Second method is used due to lack of data of certain rivers. River hydrology is obtained from nearest river then calculated using first method and scaled to real values.

Figure 2 represents a simulated hourly river discharge curve calculated by first method, for river Neretva in extremely wet year 2010, as well as average river discharge rate and discharge rate of a dry year for same river Figure 3 represents a simulated hourly river discharge curve calculated by second method, for river Vrbas in extremely wet year 2010.

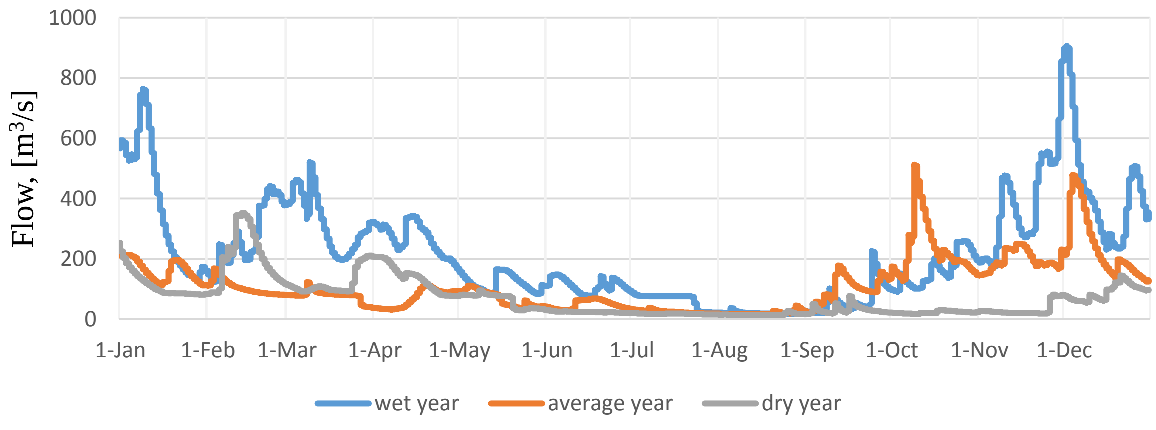

Figure 2 Hourly river flow distribution

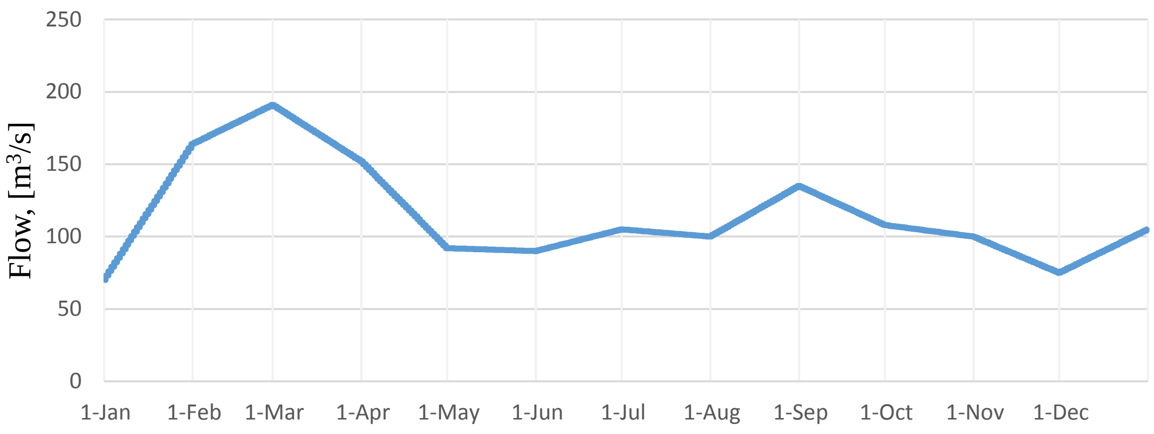

Figure 3 Modified hourly river flow distribution

2.2. Availability factor

Availability factor (AF) is used for renewable power generation units' whit no storage. This means that the power they produce is either fed to the grid or curtailed. AF describes proportion of renewable power output in accordance to nominal power capacity. This factor is defined as the time series of values in range from 0 to 1. 0 is assigned when there is no power generation of renewable unit (wind-turbines don't rotate due to lack of wind speed, photovoltaic don't generate electricity during the night, etc.) and 1 when its power output is equal to nominal power. Between 0 and 1 units operate with a reduced power output while units that are not powered by renewable energy sources are assigned with AF of 1 since their nominal production capacity is regulated through other variables such as outages [6].

AF was determined according to:

$$AF = \frac{\sum_{tr} P_{tr,h}}{\sum_{tr} P_{max\,tr}} \tag{1}$$

where $P_{tr,h}$ is power output of unit powered by renewable energy sources tr in each time interval h [MW]; $P_{max\,tr}$ maximal power of unit powered by renewable energy sources tr [MW].

Run-of-river hydropower plants are isolated example of determine AF because power output is proportional to river flow. River flow can be greater than maximal flow and in that case excess water is released from dam without passing it through the powerhouse.

Hourly power output of a run-of-river hydro power plant unit was determined according to:

$$P_{h,u} = \begin{cases} \frac{Q_{tr,h}}{Q_{max\,tr}} \cdot P_{max\,tr} & \text{if } Q_{tr,h} \leq Q_{max\,tr} \\ 1 & \text{if } Q_{tr,h} > Q_{max\,tr} \end{cases} \tag{2}$$

where $Q_{tr,h}$ is river discharge of unit powered by renewable energy sources tr in each time interval h [m^3/s]; Q_{max_u} is maximal river discharge of unit powered by renewable energy sources tr [m^3/s].

2.3. Cross border flows

Cross border flows are hourly values of physical power exchange between two neighbouring countries. They are given as an hourly time series with values expressed in MW. These values are used as historical data by processing tool which means that actual cross border flows that are simulated by the model can differ substantially from values that are entered by user.

Cross border flows were determined according to:

$$\sum_u P_{u,h} + \sum_l I_{l,h} - \sum_l E_{l,h} - Dem_{electricity_h} = 0 \tag{3}$$

where $P_{u,h}$ is power output of unit u in each time interval h [MW]; $I_{l,h}$ is sum of hourly imports between a specific country and the rest of the world (RoW); $E_{l,h}$ is sum of hourly imports between a specific country and RoW [MW]; $Dem_{electricity_h}$is hourly electricity demand of a country in each time interval h [MW].

Hourly values of exports and imports between two countries is constrained by the net transfer capacity (NTC) as follows:

$$E_{l,h} \leq NTC_l \tag{4}$$

$$I_{l,h} \leq NTC_l \tag{5}$$

Where NTC_l is net transfer capacity of transmission line l [MW].

2.4. Hydro data

Reservoir level is state of charge of hydro storage. For accumulation hydro power plants, storage level is equivalent to the hourly potential energy of water in accumulation divided by the maximal energy of storage. This factor is defined as the time series of values in range from 0 to 1. 1 is when the storage is full, and 0 when there is no storage available. [6]

Hourly values of reservoir level was determined according to:

$$RL = \frac{E_{s,h}}{E_{max_s}} \tag{6}$$

where $E_{s,h}$is energy stored in accumulation unit s in each time interval h [MWh]; $E_{max_s}$is maximal energy stored in accumulation of storage unit s [MWh].

Energy stored in accumulation unit s in each time interval h $E_{s,h}$, was determined according to:

$$E_{1,s} = E_{initial,s} + Inflow_{1,s} + \frac{Dem_{HDAM_{1,s}}}{\eta_{HDAM}} \tag{7}$$

$$E_{s,h} = E_{h-1,s} + Inflow_{s,h} + \frac{Dem_{HDAM_{s,h}}}{\eta_{HDAM}} \tag{8}$$

where $E_{initial,s}$ is initial energy stored in accumulation unit s [MWh]; $Dem_{HDAM_{s,h}}$is electricity demand of storage unit s in each time interval h [MW]; $Inflow_{s,h}$is inflow of storage unit s in each time interval h [MWh/h]; $\eta_{HDAM}$is efficiency of accumulation hydro power plant.

Inflow of storage unit s in each time interval h $Inflow_{s,h}$, was determined according to:

$$Inflow_{s,h} = \frac{Q_{s,h} \cdot \rho \cdot g \cdot h_{max_s}}{1000000} \tag{9}$$

where ρ is density of water [kg/m^3]; g is gravity constant [m/s^2]; $h_{max_s}$is maximal head of storage unit s [m].

Electricity demand of storage unit s in each time interval h $Dem_{HDAM_{s,h}}$, was determined according to:

$$Dem_{HDAM_{s,h}} = Dem_{HDAM_h} \cdot \frac{E_{prod_s}}{\sum_s E_{prod_s}} \tag{10}$$

where $Dem_{HDAM_h}$is electricity demand of all storage units in each time interval h [MW]; $E_{prod_s}$is energy produced by storage unit s in one year [GWh].

Efficiency of accumulation hydro power plant η_{HDAM}, was determined according to:

$$\eta_{HDAM} = \frac{P_{max_s} \cdot 1.000.000}{\rho \cdot g \cdot h_{max_s} \cdot Q_{max_s}} \tag{11}$$

where $P_{max_s}$is maximal power of storage unit s [MW]; $Q_{max_s}$is maximal flow of storage unit s [m^3/s].

Electricity demand of all storage units in each time interval h Dem_{HDAM_h}, was determined according to:

$$Dem_{HDAM_h} = Dem_{electricity_h} + \sum_l E_{l,h} - \sum_l I_{l,h} - \sum_u P_{HROR_{u,h}} - P_{TPP_h} \tag{12}$$

where $P_{HROR_{u,h}}$is hourly power output of run-of-river hydro unit in each time interval h [MW]; $P_{TPP_h}$is power output of all thermal power plants including steam turbine, gas turbine and combined cycle in each time interval h [MW].

Power output of all thermal power plants in each time interval h P_{TPP_h}, was determined according to:

$$P_{TPP_h} = \begin{cases} C_{TPP} \cdot \sum_u P_{u,h} & \text{if} \quad Dem_{TPP_h} > C_{TPP} \cdot \sum_u P_{u,h} \\ Dem_{STUR_h} & \text{if} \quad Dem_{TPP_h} \leq C_{TPP} \cdot \sum_u P_{u,h} \\ 0 & \text{if} \ Dem_{TPP_h} < 0{,}4 \cdot P_{min_{u,h}} \end{cases} \quad (13)$$

where C_{STUR} is correction factor for thermal power plants that has been determined iteratively; $Dem_{TPP_h}$is electricity demand of all thermal power plants in each time interval h [MW]; $P_{min_{h,u}}$ is hourly power output of thermal power plant with smallest installed power [MW].

Electricity demand of all thermal power plants in each time interval h Dem_{TPP_h}, was determined according to:

$$Dem_{TPP_h} = Dem_{electricity_h} + \sum_l E_{l,h} - \sum_l I_{l,h} - \sum_u P_{HROR_{u,h}} \quad (14)$$

2.4.1. *Scaled inflows*

Scaled inflows (SI) are flows of exogenous sources of rivers or rainfalls into storage. They have direct influence to the state of charge of reservoir. This factor must be defined as time series with values expressed in MWh/h. SI represent values of hourly river flows devided with nominal power output of hydropower plant. This parameter is defined as the time series of values in range from 0 to number that is higher then 1[6].

Scaled inflows (SI), of hydro units was determined according to:

$$SI = \frac{inflow_{u,h}}{P_{max_s}} \quad (15)$$

2.5. Outage Factors

Power plant outages are represented through Outage Factor. This factor represent planned and unplanned outages of certain power plant as well as power plant's curtailed power output. This parameter is defined as the time series of values in range from 0 to 1[6].

Outage Factor of specific power plant was determined according to:

$$OF = 1 - \frac{P_{u,h}}{P_{max_u}} \tag{16}$$

where P_{max_u} is maximal power of unit u [MW];

3. MODEL

For the purpose of this master thesis a Dispa-SET model was used. The Dispa-SET model is a unit commitment and dispatch optimization model that focuses on balancing and flexibility problems in electrical grids. Program was developed within the European Commission's science and knowledge service called Joint Research Centre (JRC). The optimisation within the model, depending on the desired level of accuracy and complexity, is defined either as a LP or MILP problem. Model uses a series of input data and optimisation variables in order to simulate intercountry or regional power systems. In order to simulate such power systems, DispaSET model needs input data with high level of detail that can as accurately as possible describe operation of such power systems. The intended use of this model is to provide support to power system operators, TSO's (transmission system operator), who have access to all technical and economic data of all the power plants within the simulated power system, as well as information of the electricity demand and the transmission network data. Once when the power system is simulated its main purpose is to point how much of backup capacity is necessary in order to safely meet demand.

3.1. Input Data

Input data is a series of documents that are located in the DispaSET database, and are being used by processing programs in order to implement an optimisation of a power system. This data is obtained through all kinds of different sources like: on-line reports, annual country reports, technical documentations, books, newspaper articles, books etc. All input data that is written as a time series must be registered with their proper time value that is relative to the UTC time zone. All available technology dependent power plants must be used in accordance to DispaSET convention.

3.2. Countries

DispaSET processing tools use ISO 3166-1 standard to describe each country. The list of countries are shown in Table 1.

Table 1 List of Dispa-SET country names

Code	Country
AL	Albania
BA	Bosnia and Herzegovina
BG	Bulgaria
HR	Croatia
ME	Montenegro
MK	Macedonia
RO	Romania
SR	Serbia
XK	Kosovo

3.3. Technologies

DispaSET processing tools distinguish different technologies of certain plant in accordance to Table 2.

Table 2 List of Dispa-SET technologies [6]

Technology	Description
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

3.4. Fuels

DispaSET processing tools distinguish different fuel types in accordance to Table 3.

Table 3 List of Dispa-SET fuels [6]

Fuel	Examples
BIO	Bagasse, Biodiesel, Gas From Biomass, Gasification, Biomass, Briquettes, Cattle Residues, Rice Hulls Or Padi Husk, Straw, Wood Gas, Wood Waste Liquids etc.
GAS	Blast Furnace Gas, Boiler Natural Gas, Butane, Coal Bed Methane, Coke Oven Gas, Flare Gas, Gas, Methane, Mine Gas, Natural Gas, Propane, Refinery Gas, Sour Gas, Synthetic Natural Gas, Top Gas, Waste Gas, Wellhead Gas etc.
GEO	Geothermal steam
HRD	Anthracite, Bituminous Coal, Coker By-Product, Coal Gas, Coke, Coal, Coal-Oil Mixture, Other Coal, Coal And Pet Coke, Anthracite Coal Waste, Gobe, Imported Coal, Other Solids, Soft Coal, Anthracite Silt, Steam Coal, Subbituminous, Pelletized Synthetic Fuel From Coal, Bituminous Coal Waste etc.
HYD	Hydrogen
LIG	Lignite black, Lignite brown, lignite
NUC	U, Pu
OIL	Crude Oil, Distillate Oil, Diesel Fuel, 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, Petroleum Coke, Petroleum Coke Synthetic Gas, Black Liquor, Re-Refined Motor Oil, Oil Shale, Waste Oil etc.
PEA	Peat Moss
SUN	Solar energy
WAT	Hydro energy
WIN	Wind energy
WST	Digester Gas, Gas From Refuse Gasification, Hazardous Waste, Industrial Waste, Landfill Gas, Manure, Medical Waste, Refused Derived Fuel, Waste Paper And Waste Plastic, Refinery Waste, Tires, Agricultural Waste, Waste Coal, Waste Water Sludge, Waste etc.

3.5. Power plants

Power plants input data is a series of data that includes general and technical information about all power plants in model. List of data that describes certain power plants is presented in Table 4.

Table 4 Common input field for all units

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

3.5.1. Storage Units

Power plant or units that are either connected to or have an integrated storage need, beside common input data, additional data that describes their storage. Additional data are presented in Table 5.

Table 5 Additional data for storage units

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

3.5.2. CHP Units

Power Power plant or units that work as CHP (combined heat and power) must contain, beside common input data, additional data that include information about their CHP. Additional data are presented in Table 6.

Table 6 Additional data for CHP units

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

3.6. Availability Factor

Availability factor (AF) is used for renewable power generation units' whit no storage. This means that the power they produce is either fed to the grid or curtailed. AF describes proportion of renewable power output in accordance to nominal power capacity. This factor is defined as the time series of values in range from 0 to 1. 0 is assigned when there is no power generation of renewable unit (wind-turbines don't rotate due to lack of wind speed, photovoltaic don't generate electricity during the night, hydropower plant with no river flow lower etc.), and 1 when it's power output is equal to nominal power. Between 0 and 1 units operate with reduced power output Units that are not powered by renewable energy sources are assigned AF of 1 since their nominal production capacity is regulated through other variables such as outages[6].

3.7. Hydro Data

3.7.1. Scaled inflows

Scaled inflows (SI) are flows of exogenous sources of river lows or rainfalls. They have direct influence to the state of charge of reservoir. This factor must be defined as time series with values expressed in MWh/h. SI represent values of hourly river flows divided with nominal power output of hydropower plant. Values are in range from 0 to number that is higher than 1. Between 0 and 1

Scaled inflows should be provided in the form of time series with the unit name or the technology as columns header[6].

3.7.2. Reservoir level

Reservoir level is state of charge of hydro storage. For accumulation hydro power plants, storage level is equivalent to the hourly potential energy of water in accumulation divided by the maximal energy of storage. This factor is defined as the time series of values in range from 0 to 1. 1 is when the storage is full, and 0 when there is no storage available. This input data is important because emptying the storage has no cost, and optimisation tends to set storage level to 0 at the end of the optimisation period[6]

3.8. Outage Factor

Power plant outages are represented through Outage Factor. This factor represent planned and unplanned outages of certain power plant as well as power plant's curtailed power output. This parameter is defined as the time series of values in range from 0 to 1. 0 is when the power plant have no outage, which means power production whit nominal power, and 1 when power plant is in full outage with no power production[6]

3.9. Net transfer capacities

Net transfer capacities (NTC) are values of transmission capacities between neighbouring countries. This values represent maximal power that can be sent or received within two countries. Because NTC values can vary in time, this factor is also defined as time series of hourly values expressed in MW. Due to unsymmetrical power flow of transmission lines, NTC values can be different in both directions, and because of that it must be expressed in both directions. NTC values must be provided as follows: NTC capacity from Serbia to Montenegro is expressed as “RS -> ME” and from Montenegro to Serbia “ME -> RS”[6].

3.10. Cross Border Flows

Cross Border Flows are physical flows of electricity between neighbouring countries. This factor is defined as time series with values expressed in MW. These values are used as historical data by processing tool which means that actual cross border flows that are simulated by the model can differ substantially from values that are entered by user. If cross border flows are not defined, system will be considered as islanded[6].

3.11. Fuel prices

Fuel prices are different in every country and may vary in time, therefore it is provided as time series of values expressed in €/MWh. Fuel prices can be provided as same values for all simulated zones[6]

3.12. Load Real-time

This factor represent hourly consumption of electricity by simulated zone. It is provided in time series of values expressed in MW[6].

3.13. Optimisation variables

Optimisation variable are shown in Table 7. And they are used for establishing cross border flows, unit commitment, filling or emptying storage, minimizing the total power system costs, demand related constraints

Table 7 List of optimisation variables [6]

Name	Description	Units
Committed(u,h)	Unit committed at hour h {1,0}	n.a
CostStartUpH(u,h)	Cost of starting up	EUR
CostShutDownH(u,h)	cost of shutting down	EUR
CostRampUpH(u,h)	Ramping cost	EUR
CostRampDownH(u,h)	Ramping cost	EUR
CurtailedPower(n,h)	Curtailed power at node n	MW
Flow(l,h)	Flow through lines	MW
MaxRamp2U(u,h)	Maximum 15-min Ramp-up capbility	MW/h
MaxRamp2D(u,h)	Maximum 15-min Ramp-down capbility	MW/h
Power(u,h)	Power output	MW
PowerMaximum(u,h)	Power output	MW
PowerMinimum(u,h)	Shed load	MW
ShedLoad(n,h)	Shed load	MW
StorageInput(s,h)	Charging input for storage units	MWh
StorageLevel(s,h)	Storage level of charge	MWh
Spillage(s,h)	Spillage from water reservoirs	MWh
SystemCostD	Total system cost for one optimization period	EUR
LostLoadMaxPower(n,h)	Deficit in terms of maximum power	MW
LostLoadRampUp(u,h)	Deficit in terms of ramping up for each plant	MW
LostLoadRampDown(u,h)	Deficit in terms of ramping down	MW
LostLoadMinPower(n,h)	Power exceeding the demand	MW
LostLoadReserve2U(n,h)	Deficit in reserve up	MW

3.14. Optimisation model

As said before, optimisation model aims to solve the unit commitment problem with a high level of detail. It describes the operation of large-scale power systems and scheduling of available generation units in order to minimise the total costs of running the power system.

The total costs are sum of all the costs that are related to the certain units and technologies. The total cost include: fixed and variable costs, start-up and shut-down costs and ramping costs (ramp-up and ramp-down) etc. The model simulates simplified example of problem faced by power system operators.. The main constraints of the model are supply and demand balances that have to be covered in every time step and for each zone. The power outputs of committed generation units are bounded by their minimal and maximal electricity production limits. In order to increase lifetime of generating units once a unit is started up it cannot shut down immediately . Also, when a generating unit is shut down it cannot start up instantly. There are also some additional constrains applied to the units that are connected to a storage unit. This constraints include storage capacity, inflow into the storage, outflow out of the storage, charging capacity as well as charging and discharging efficiencies. Network related constrains are related to maximal power flows between the two countries, that are limited by the capacity of transmission lines. Model also has the ability to cluster some units that are powered by same technology into a larger one. This reduces the number of continuous and binary variables with a purpose of 19increasing the computational efficiency[6]

4. INPUT DATA

In this section all the input data is described in more detail. Three scenarios have been developed. One reference scenario and two alternatives. For the reference scenario the year 2010 has been chosen due to the data availability. Alternative scenarios are made for the year 2020 and 2030. Each of alternative scenarios has three cases. Cases A and B are developed according to the national reports of each country. These two case are identical and the only difference is that the Case B works in the island regime. The Case C is a strategy with high penetration of renewable energy sources in to the power sector. The main goal of developing scenarios is to validate each strategy obtained from national reports, and to see behaviour of power systems in the future. Another target is to see how penetration of RES effects power systems. All this is important in order to reduce GHG emissions and imports from the surrounding countries, improve stability of the power system and security of supply as well as increase energy independency.

4.1. Fuel prices

All Western Balkan countries share similar values of fuel prices. Because of that same fuel prices have been adopted for all simulated zones inside the Wester Balkan region. All power plants from the Reference scenario are powered either by lignite or natural gas and their prices are described in more detail in the next chapter.

4.1.1. Gas prices

Due to small share of gas fired units in the total installed capacities of all the units and technologies, gas price has been calculated as a mean value of historical gas prices from the EU gas hub[9]. Gas prices are obtained as daily values of market prices and converted in hourly values using linear interpolation. Both hourly prices and mean price are illustrated in Figure 4. The average price of gas is 22,21 EUR/MWh and this value is used for calculations throughout all scenarios.

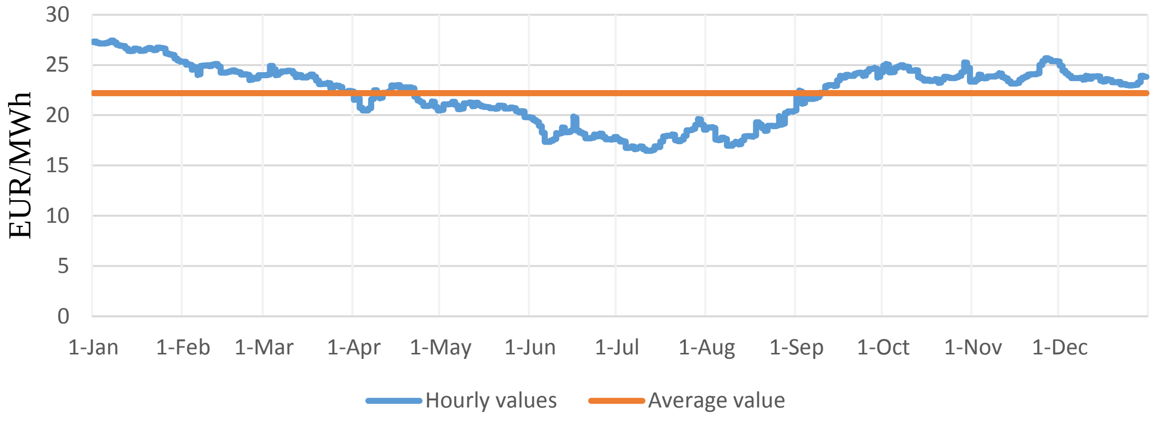

Figure 4 Hourly values of gas prices

4.1.2. Coal and lignite prices

Every country within Western Balkans is producing coal and lignite from its own mines. Lignite is the most common local fossil fuel in terms of volume and employees high working force. Lignite is regarded as the national tresury which is the reason why governments supportlignite production. In order to ensure jobs for local population and boost the economy mines are being subsidised by government. Subsidy system in all countries is complex and not fully reported in fiscal energy statistics[10].

4.2. Cross border flows

Cross Border Flows are physical flows of electricity between the two neighbouring countries. These values are used as historical data by processing tool which means that actual cross border flows that are simulated by the model can differ substantially from the values that are entered by user. If cross border flows are not defined, system will be considered as an island. Hourly values of cross border flow are obtained from EU Transparency platform and modify according to (3), (4) and (5) [11].

4.3. Net transfer capacities (NTC)

4.3.1. Reference

Net transfer capacities for Europe are obtained and imported into model as hourly values expressed in MW [12]. Their values have been obtained from various different sources and where not available calculated according to the voltage level in the transmission lines[13][14].

NTC values for Western Balkan countries can be seen inTable 8. From there it is clear that the highest NTC capacitiy are between BA and ME and BA and RS. Lowes NTC value is between ME and RS, AL and ME and AL and XK. Albania has worst interconnection to neighbouring countries and could potentially have problems in therms of security of supply.

Table 8 NTC for Western Balkan countries in 2010

	AL	BA	ME	MK	RS	XK
AL	0	0	210	0	0	210
BA	0	0	600	0	600	0
ME	210	600	0	0	210	400
MK	0	0	0	0	0	400
RS	0	600	210	0	0	600
XK	210	0	400	400	600	0

NTC values between Western Balkans countries and Europe are presented in Table 9. It is clear that the RS has best connections to neigbouring countries outside of Western Balkans region and could be potentially be regarded as a balancing center for the whole region. Lowest NTC value is between RS and HR. Kosovo and Montenegro have no interconnections with countries outside Western Balkans region because they have national borders only with countries within Western Balkans.

Table 9 NTC between Western Balkan countries and Europe

	BA	ME	RS	XK
HR	600	0	350	0
BG	0	0	450	0
RO	0	0	700	0
HU	0	0	600	0

4.3.2. Alternative scenarios

NTC values for future scenarios have been obtained from various different sources and where not available calculated according to the voltage level in the transmission lines[15][14]. NTC's for 2020 are shown in Table 10, and NTC values for 2030 are presented in Table 11.

Table 10 NTC for Western Balkan countries in 2020

	AL	BA	ME	MK	RS	XK
AL	0	0	210	0	0	700
BA	0	0	400	0	600	0
ME	210	400	0	0	210	400
MK	0	0	0	0	400	800
RS	0	600	210	400	0	600
XK	700	0	400	800	600	0

Table 11 NTC for Western Balkan countries in 2030

	AL	BA	ME	MK	RS	XK
AL	0	0	210	0	0	700
BA	0	0	400	0	1.400	0
ME	210	400	0	0	1.100	400
MK	0	0	0	0	400	800
RS	0	1.400	1.100	400	0	600
XK	700	0	400	800	600	0

From the national strategies it can be seen that interconnection lines and capacities are increasing. Highes improvements should be made betwen Serbia and Bosnia and Herzegovina and Serbia and Montenegro. New interconnection lines are build between Montenegro and Macedonia. With higer NTC values security of supply, and stability of the Western Balkan region are improved.

4.4. Montenegro

The capital city and at the same time the largest city of Montenegro is Podgorica. According to national census population of Montenegro in 2010 was 618.757 people [16]. Montenegro has borders with Croatia, Bosnia and Herzegovina, Serbia, Kosovo and Albania. Montenegro has a coastline and acces to the Mediterranean Sea through Adriatic Sea. Figure 5 shows transmission network of Montenegro as well as position of larger power plants and substations in 2010. Relativly uniform electricity demand is established during the whole year. The year 2010 was a year with high amount of percitipations which have great influence on electricity production from hydropower plants. Montenegro has two large substations located near cities of Podgorica and Pljevlja. It can be seen that Montenegro has 400 kV transmission lines between Bosnia and Herzegovina and Kosovo. With Serbia and Albania, Montenegro is connected through 220 kV transmission lines.

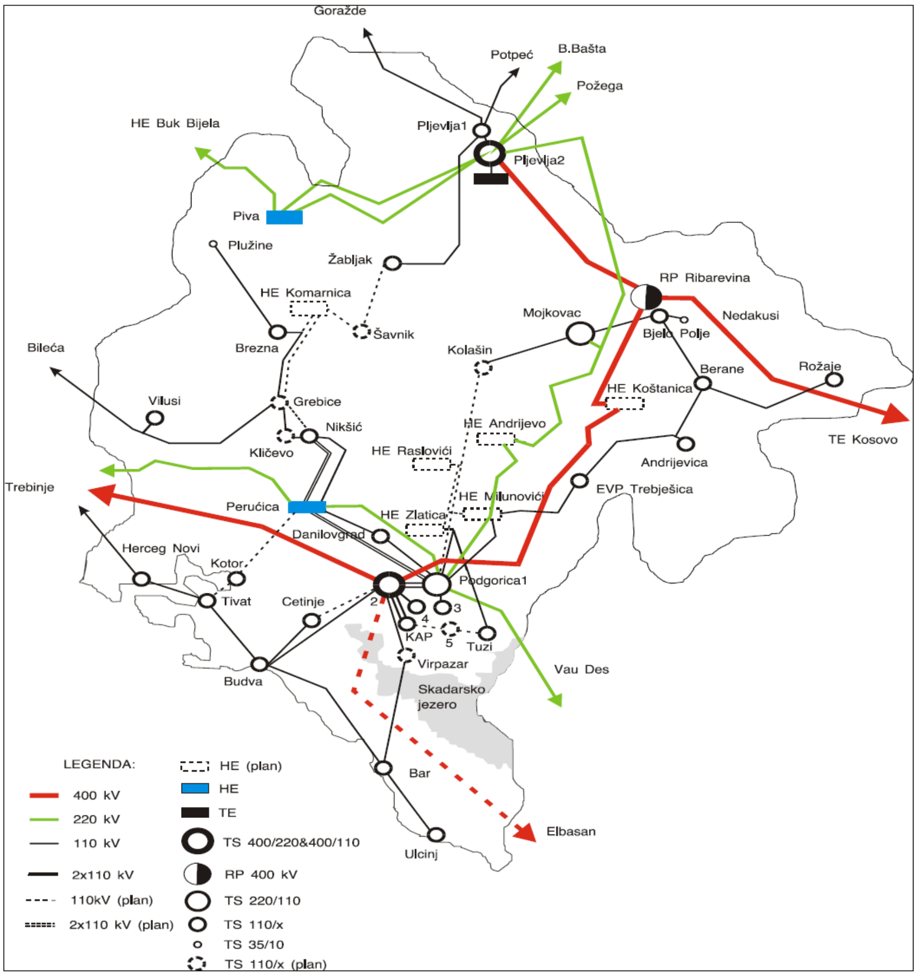

Figure 5 Transmission network of Montenegro and position of larger power plants and substations[17]

4.4.1. *Electricity demand*

4.4.1.1. Reference scenario

The electricity demand of Montenegro is presented in Figure 6. Overall annual electricity consumption of Montenegro in year 2010 amounted to 3.925,07 GWh [18]. During the winter months it is slightly higher than in summer due to the fact that almost 60% of population is using electricity for space heating [19]. Highest demand of 665 MW has been recorded during

January while the lowest is 203 MW and recorded in June. Electricity demand vary between 300 MW and 600 MW with average value of 448 MW.

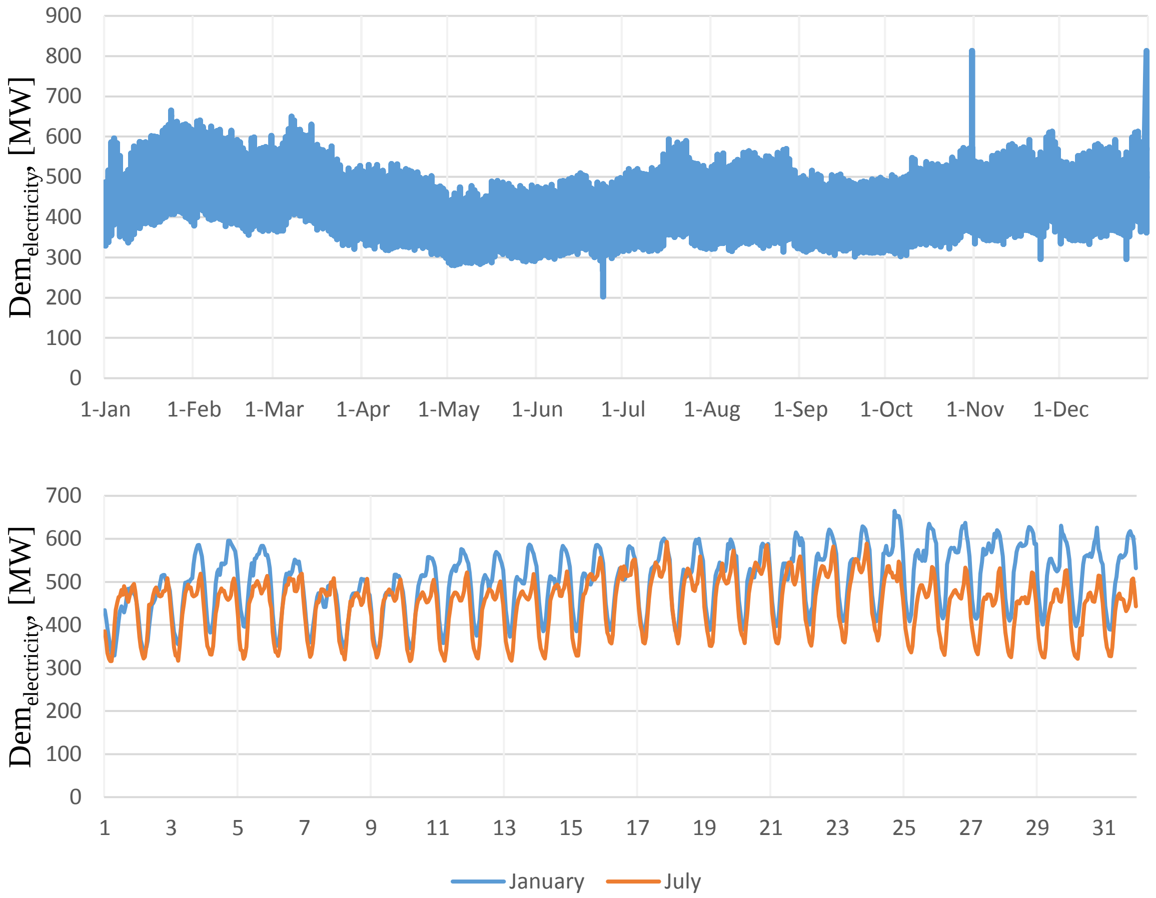

Figure 6 Hourly electricity demand of Montenegro

4.4.1.2. Alternative scenarios

Electricity demand of Montenegro in 2020 is 4.290 GWh, and in 2030 is 4.270 GWh [20]. Hourly values of electricity demand presented in Figure 6 are scaled and used in future scenarios. Electricity demand rise from 2010 to 2020 and then fall from 2020 to 2030. Electricity demand of one year is same for all three scenarios.

4.4.2. Electricity production

4.4.2.1. Reference scenario

The electricity production in Montenegro in 2010 consist of electricity produced by thermal power plants and hydropower plants. List of electricity generating units can be seen in Table

12. Total installed capacity in 2010. was 895,126 MW of witch 210 MW is thermal power plans, 673 MW are accumulation hydropower plants, and 12,156 MW are small run-of-river hydropower plants. Installed capacities in 2010 are sufficient to cover peak loads because highest electricity demand is 665 MW and total installed capacity is 895,126 MW which is higher then maximal demand by 230 MW. Highest share of installed capacities have accumulation hydropower plants and it amounts to 75,18%. Thermal power plants accounted for 23,46% of total installed capacities and run-of-river have smallest share of 1,36%. HE Piva is largest power plant in Montenegro with installed power of 360 MW or 40,22% of total installed capacity.

Table 12 List of power plants in Montenegro

Unit	Power Capacity MW	Technology	Fuel	
HE Piva	360	HDAM	WAT	[21]
HE Perucica	310	HDAM	WAT	
TE Pljevlja	210	STUR	LIG	
HE Pljevlja	2.961	HDAM	WAT	[22]
HE Glava Zete	6.4	HROR	WAT	[23]
HE Slap Zete	2.4	HROR	WAT	
HE Muskovica Rijeka	1.95	HROR	WAT	
HE Savnik	0.2	HROR	WAT	
HE Lijeva Rijeka	0.1	HROR	WAT	
HE Podgor	0.465	HROR	WAT	
HE Rijeka Crnojevica	0.65	HROR	WAT	

4.4.2.2. Thermal power plants

There is only one thermal power plant in Montenegro, TE Pljevlja with total installed capacity of 210 MW. Power plant flexibility data are calculated according to some scientific publications and are presented in Table 13. In addition to this, data related to the costs of running and operating units is also covered by the same publications[24][25]. Nominal efficiency of TE Pljevlja amounts to 34%, minimal efficiency is 29%, ramp up and ramp down rate amounts to 2,5% of nominal power per minute. Table 14 shows cost related data for thermal power plants in Montenegro from where it is clear that start up cost for TE Pljevlja is 21.892 EUR.

Table 13 Technology related data for thermal power plants in Montenegro[24]

		Unit
Variable		TE Pljevlja
Efficiency	**%**	0,34
Min Up Time	**h**	6
Min Down Time	**h**	1,5
Ramp Up Rate	**%/min**	0,025
Ramp Down Rate	**%/min**	0,025
Min Part Load	**%**	0,25
Min Efficiency	**%**	0,29
Start Up Time	**h**	6
CO2 Intensity	**kg/MW**	1.061

Table 14 Cost related data of thermal power plants in Montenegro[25]

		Unit
Variable		TE Pljevlja
Start Up Cost	**€**	21.892
No Load Cost	**€**	0
Ramping Cost	**€**	1.8

Acordin to national report of Montenegro planed outage due to the maintenance of TE Pljevlja is scheduled from April til June [26]. During this period TE Pljevlja was not able to produce electricity. The hourly values of outage factor for TE Pljevlja are determined according to (16), and graphical representation of outages are illustrated in Figure 7. Total annual electricity production of TE Pljevlja in 2010 was 1271,7 GWh or 31,62% of total electricity production [27].

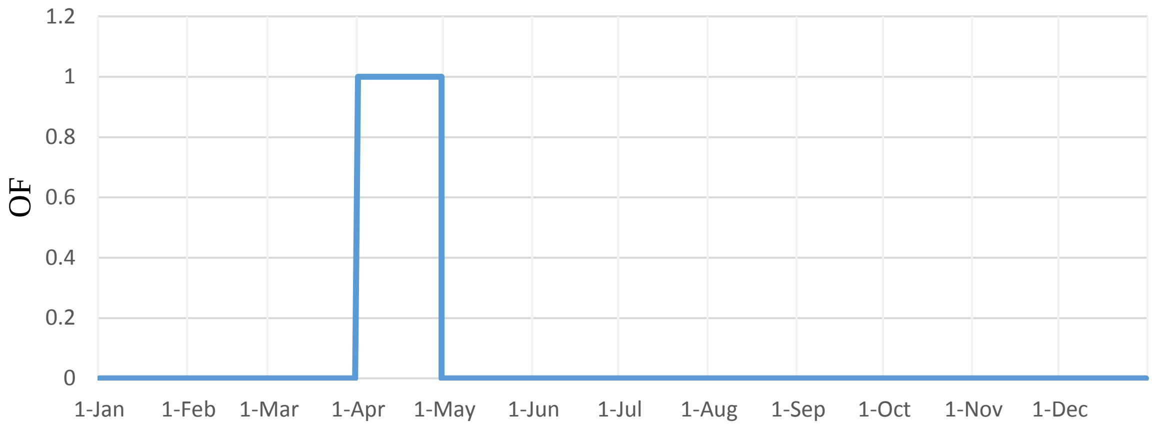

Figure 7 Hourly values of outage factor for TE Pljevlja

4.4.2.3. Hydropower plants

There are three accumulation hydropower plants in Montenegro. Two of them are large, HE Piva located on the river Piva, with total installed capacity of 360 MW and HE Peručica on river Glava Zete, with total installed capacity of 310 MW. The HE Pljevlja located on the river of Otilovici has installed capacity of 2,961 MW. The total installed capacity of all small run-of-river hydropower plants is 12,165 MW. Technology related data for hydropower plants are determined from various sources and calculated where not available. In Table 15 are presented technology related data for hydropower plants from where it is clear that maximal efficiency amounts to 85% and minimal efficiency amounts to 50%. Values fot HE Piva and HE Perućica are apllied to all hydropower plansts in Montenegro. Total annual electricity production of hydropower plants in 2010. was 2749,6 GWh or 68,38% of total electricity production, of which HE Perucica produced 1434,9 GW or 35,68% of total production and HE Piva produced 1285,8 GWh or 31,97% of total production.

Table 15 Technology related data for hydropower plants in Montenegro

		Unit	
Variable		HE Piva	HE Perucica
Efficiency	**%**	0,85	0,85
Min Up Time	**h**	0	0
Min Down Time	**h**	0	0
Ramp Up Rate	**%/min**	1	1
Ramp Down Rate	**%/min**	1	1
Min Part Load	**%**	0	0
Min Efficiency	**%**	0,5	0,5
Start Up Time	**h**	1	1
CO2 Intensity	**kg/MW**	0	0

Technical data of power plants is presented in Table 16 from where it is clear that HE Piva have largest accumulation with volume of 880.000.000 m^3 and HE Pljevlja have smallest accumulation with volume of 18.000.000 m^3. HE Piva have large installed flow with not so high nominal head while HE Perucica have high nominal head and low installed flow.

Table 16 Technical data of hydropower plants in Montenegro

Unit	Nominal power	Installed flow	Nominal head	Accumulation volume [m3]	Energy in accumulation	
	MW	**m^3/s**	**m**	**m^3**	**MWh**	
HE Piva	360	240	150	880.000.000	359.700	[21]
HE Perucica	310	68	549	148.000.000	221.411,7	
HE Pljevlja	2,961	9	43	18.000.000	2.109,15	[22]
HE Glava Zete	6,4	29	21,5			[23]
HE Slap Zete	2,4	26	7			
HE Muskovica Rijeka	1,95	1,05	160			
HE Savnik	0,2	1	26			
HE Lijeva Rijeka	0,1	0,22	40,8			
HE Podgor	0,465	0,9	54			
HE Rijeka Crnojevica	0,65	3	22,7			

The availability factors for hydropower plants HE Glava Zete and Pljevlja, have been calculated according to equations (1) and (2). The graphical presentation of these AF's is presented in Figure 8. It is clear that from October til May run-of-river hydropower plants operate at full capacity because of the high river discharge rates. From May til October there are some oscilations caused by low inflows due to the low percitipations during the summer.

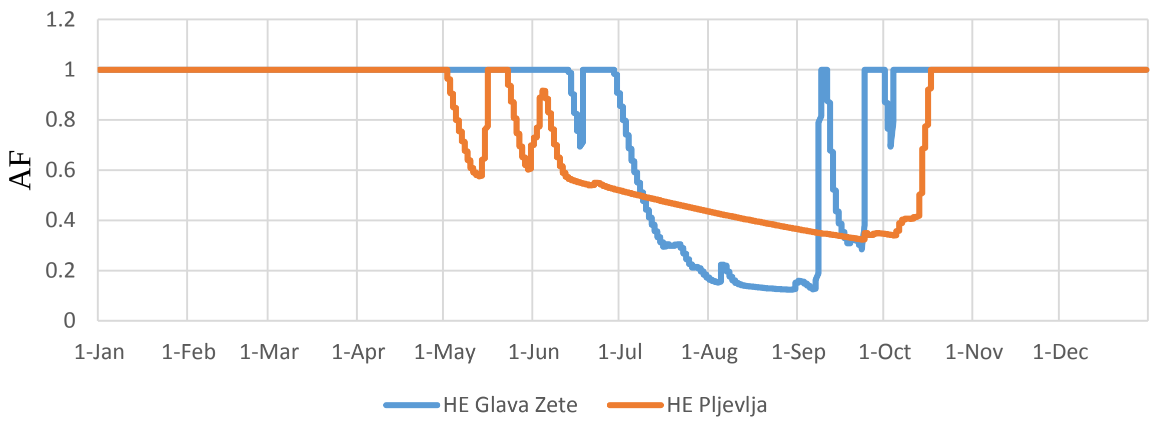

Figure 8 Hourly values of availability factor for run-of-river hydropower plants in Montenegro

RL for each accumulation hydropower plant in Montenegro is determined according to equation (6). RLs of HE Piva, HE Perucica and HE Pljevlja are shown in Figure 9. From there it can be seen that HE Perucica and HE Pljevlja have similar accumulation levels throughout the year. The main reason for that is the combination of similar river hydrologies and different electricity production. All three of them reach minimum accumulation levels between September and November mainly due to the low inflows and relatively high electricity demand during the summer. HE Piva has low level of accumulation in April because of planned overhauls in TE Pljevlja which cause higher power outputs from the accumulation hydropower plants.

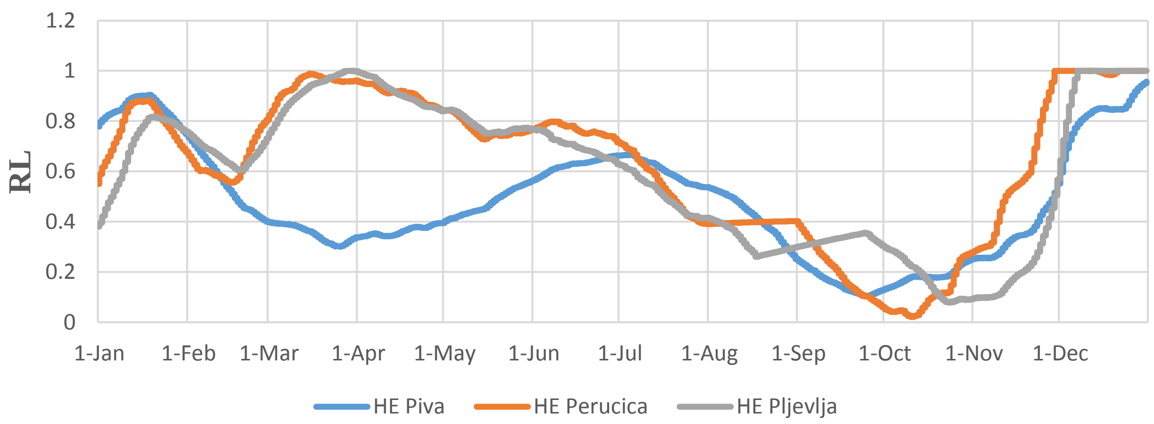

Figure 9 Hourly values of reservoir level for accumulation hydropower plants in Montenegro

Scaled inflows that have been calculated according to equation (15) are presented in Figure 10. Scaled inflows are in direct correlation with river discharge rates. Because of that, higher values usually occure during the spring and winter months, especially during the December where their values are often higher than 1. The lowest values of scaled inflows usually occure from June to October when river discharge rates are the lowest.

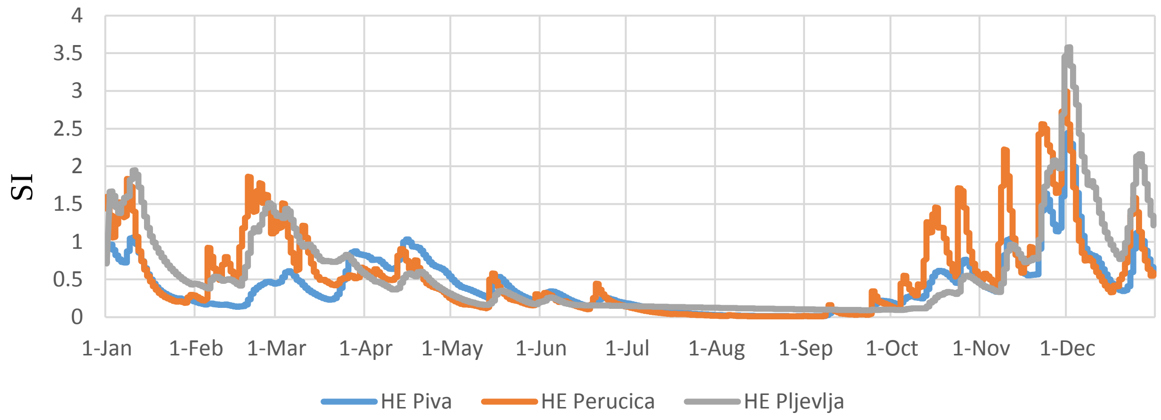

Figure 10 Hourly values of scaled inflows for accumulation hydropower plants in Montenegro

4.4.2.4. Alternative scenarios

This section describes new production capacities installed in 2020 and 2030 according to the cases A, B and C [28]. In addition to the list of power plants presented in Table 12, in Table 17 are new capacities of power plants in 2020 presented. They are added to existing ones from the Reference scenario. New capacities in 2030 are presented in Table 18. Simmilar as before they are also added to the existing ones from the reference scenario. Case C has no new thermal power plants because it is high RES scenario. Instaled capacities of wind and solar power plants are increasing in future. All technology and cost related data for new power plants are determined according to some scientific publications and imported into model[25][24].

Table 17 New capacities of Montenegro in 2020

	Case A and B	case C
	MW	MW
Hydropower plants	85	85
Thermal power plants	575	-
Solar power plants	10	25,06
Wind power plants	151,2	363,5
Total	736,2	473,56

Table 18 New capacities of Montenegro in 2030

	Case A and B	case C
	MW	MW
Hydropower plants	506	506
Thermal power plants	800	-
Solar power plants	30	363,5
Wind power plants	190	363,5
Total	1.526	1.233

AF for solar power plants is illustrated in Figure 11. Hourly values of power outputs for solar power plants are obtained from Renewables ninja and corrected using values of global irradiation from pvgis[29][30]. Corected values of hourly power output for solar power plants are representing AFs and are used in 2020 and 2030 in all three cases. The electricity production of solar power plant is oscilating on daily basis because solar power plants are producing electricity only during the day. Highest electricity production is achived in spring because in that period there are lot of sunny days. Low production with high oscilations are in winter because days are cloudy with often precipitations.

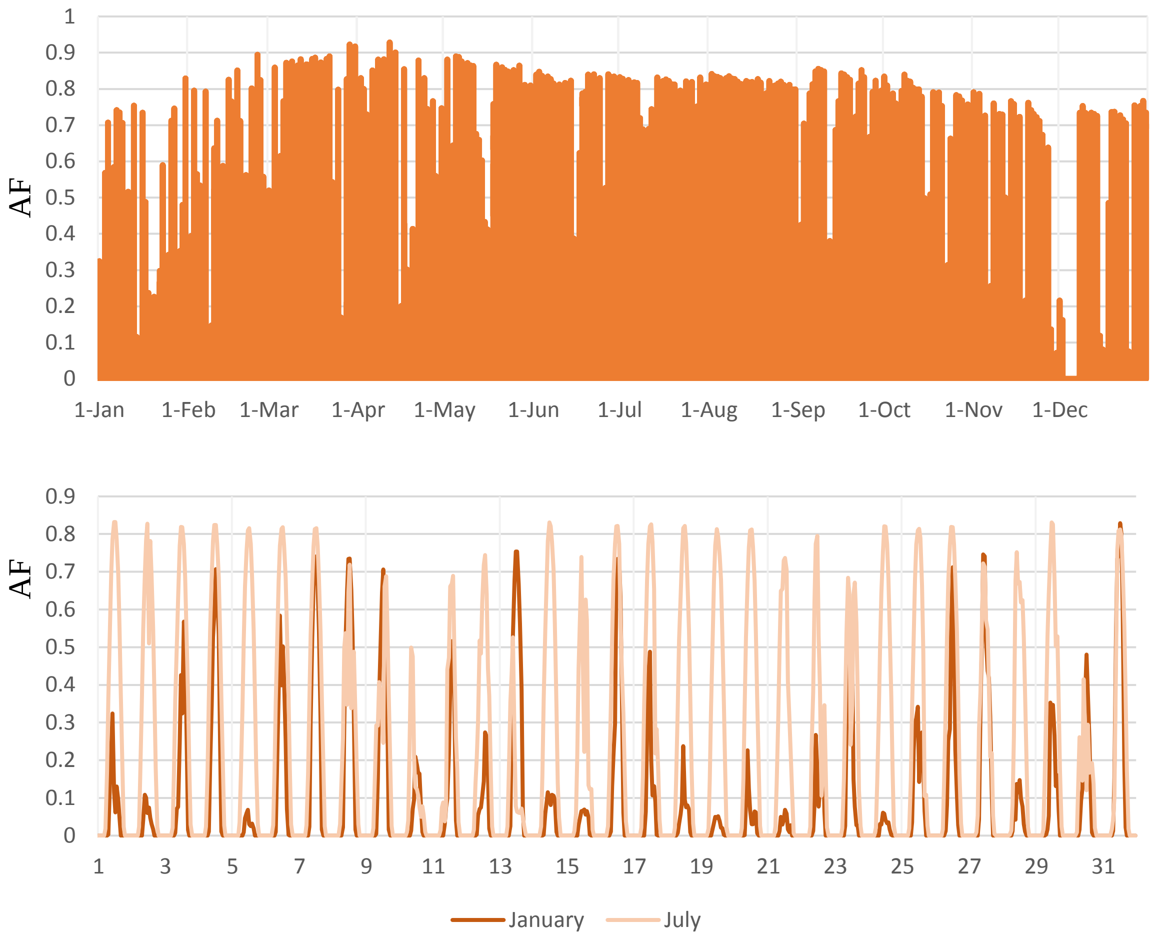

Figure 11 Hourly values of availability factor for solar power plants in Montenegro

AF for wind power plants can be seen in Figure 12. Hourly values of power output for wind power plants are obtained from Renewables ninja and they represent AF used in 2020 and 2030 for all three scenarios [29]. It is clear that from mid-may till September wind power plants operate at lower values due to the lack of wind during summer. During the whole year there are oscilations in power production from wind turbine because of stohactic nature of wind.

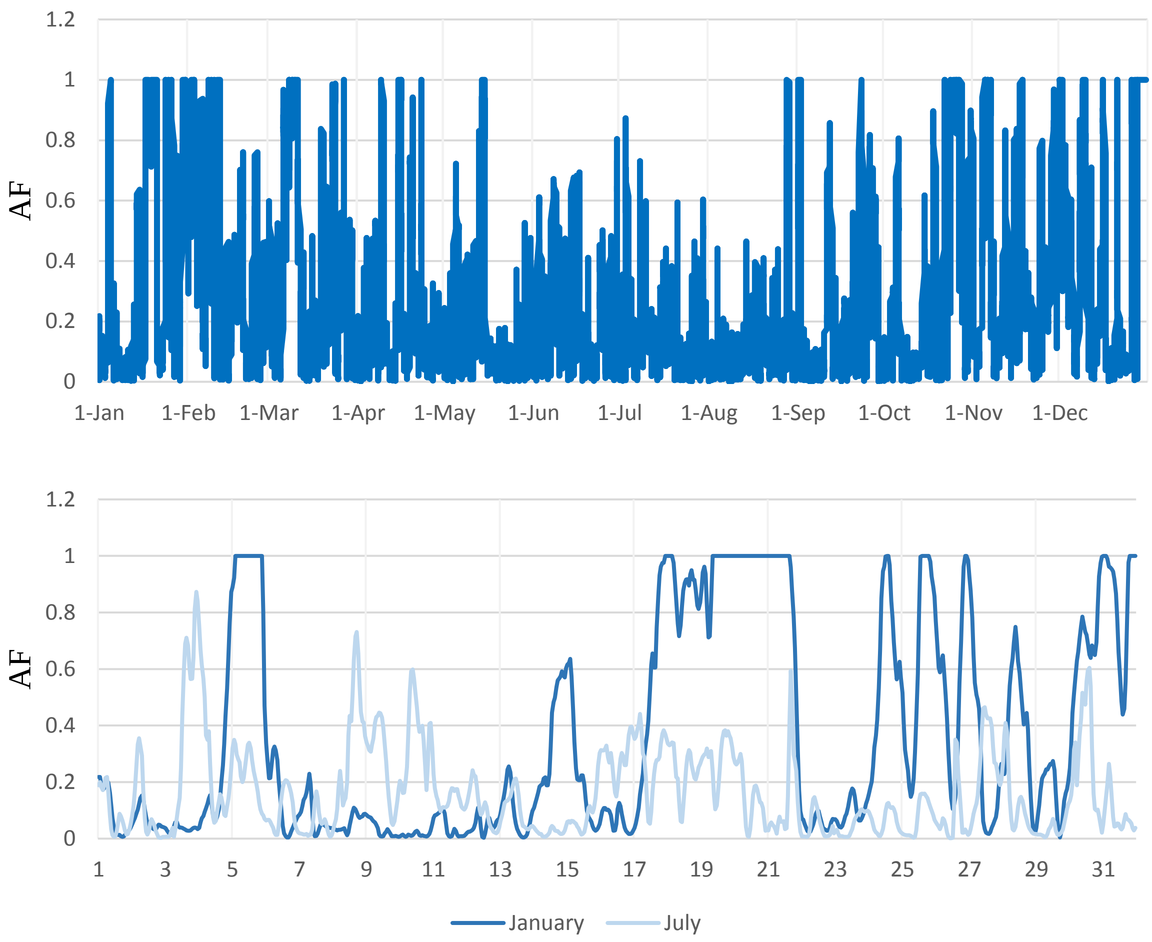

Figure 12 Hourly values of availability factor for wind power plants in Montenegro

4.5. Bosnia and Herzegovina

The capital city and at the same time the largest city of Bosnia and Herzegovina is Sarajevo. Acording to national census population in 2010 is 3.835.258 [19] Bosnia and Herzegovina have borders with Croatia, Montenegro and Serbia Figure 13 shows transmission network of Bosnia and Herzegovina as well as position of larger power plants and substations as they were in 2010. Bosnia and Herzegovina is spcefic because it has three independed power system operators (PSO), ERS, EPHZHB and EPBiH[31][32][33]. Area of activity for each PSO is illustrated in Figure 13. Relativly uniform electricity demand is established during the whole year. The year 2010 was a year with high amount of percitipations which had great influence on electricity production from hydropower plants Bosnia and Herzegovina have 400 kV transmission system within its neighbouring countries Croatia, Serbia and Montenegro. Several large substations have been located all over the country

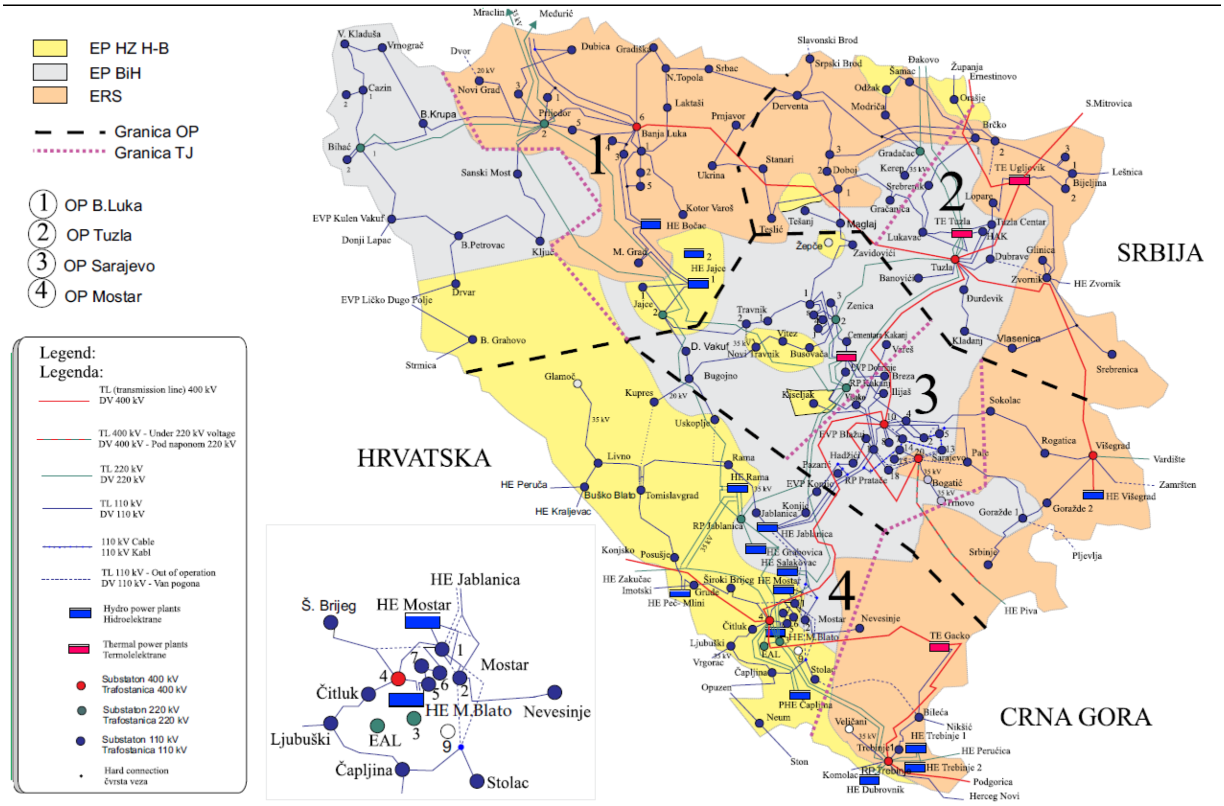

Figure 13 Transmission network of Bosnia and Herzegovina, and position of larger power plants [34]

4.5.1. Electricity demand

4.5.1.1. Reference scenario

The electricity demand of Bosnia and Herzegovina is presented in Figure 14. Overall annual electricity consumption of Montenegro in year 2010 amounted to 12.074,93 GWh[18]. During the winter months it is slightly higher than in summer due to the fact that almost 5% of population is using electricity for space heating [35]. Highest demand of 2.173 MW has been recorded during December while the lowest is 816 MW and recorded in May. Electricity demand varies between 900 MW and 1.800 MW with average value of 1.378 MW.

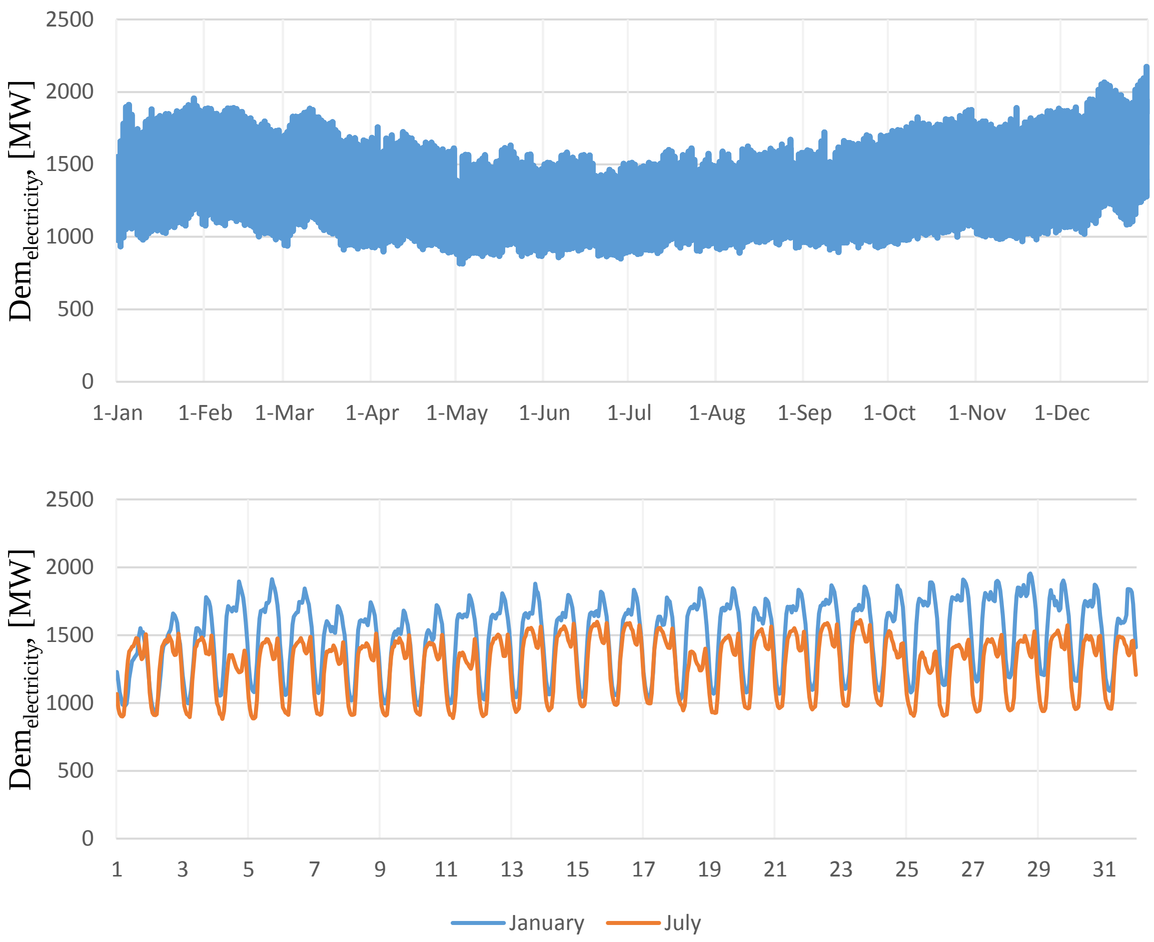

Figure 14 Hourly values of electricity demand of Bosnia and Herzegovina

4.5.1.2. Alternative scenarios

According to demand forecasts for the year 2020 and 2030 electricity demandin Bosnia and Herzegovina should be 16.110 GWh and 16.550 GWh respectivley [20]. The hourly values of electricity demand presented in Figure 14 are scaled and used in all three scenarios whitihin a specific year. From there it is clear that demand in Bosnia and Herzegovina is increasing from 2010 to 2030.

4.5.2. Electricity production

4.5.2.1. Reference scenario

The electricity production in Bosna and Herzegovina in 2010 consist of electricity produced by thermal power plants and hydropower plants. A list of electricity generating units can be seen in Table 19. The total installed capacity in 2010 was 3.622,558 MW of witch 1.534 MW are thermal power plans, 1.680 MW are accumulation hydropower plants, and 408,558 MW are run-of-river hydropower plants. Installed capacities in 2010 are sufficient to cover peak loads because highest electricity demand is 2.173 MW and total installed capacity is 3.622,558 MW which is higher then maximal demand by 1.449,558 MW. Highest share of total installed capacities have hydropower plants and they amount to 46,38%. Thermal power plants accounted for 42,35% of total installed capcacities and run-of-river power plants have smallest share of 11,27%. TE Tuzla is largest power plant in Bosnia and Herzegovina with installed power of 630 MW or 17,39% of total installed capacity.

Table 19 List of power plants in Bosnia and Herzegovina

Unit	Power Capacity MW	Technology	Fuel	
TE Tuzla	630	STUR	LIG	[36]
TE Kakanj	385	STUR	LIG	
TE Ugljevik	264	STUR	LIG	
TE Gacko	255	STUR	LIG	
HE Trebinje 1	168	HDAM	WAT	[37]
HE Grabovica	114	HROR	WAT	[38]
HE Salakovac	210	HDAM	WAT	
RHE Jablanica	181	HDAM	WAT	
RHE Capljina	420	HPHS	WAT	[39]
HE Visegrad	315	HDAM	WAT	[40]
HE Rama	160	HDAM	WAT	[41]
HE Bocac	110	HDAM	WAT	[42]
HE Dubrovnik	108	HDAM	WAT	[43]
HE Mostar	72	HROR	WAT	[44]
HE Mostarsko Blato	60	HROR	WAT	
HE Jajce 1	60	HROR	WAT	[45]
HE Jajce 2	30	HROR	WAT	

<table>
<tr><th rowspan="2">Unit</th><th>Power Capacity</th><th rowspan="2">Technology</th><th rowspan="2">Fuel</th><th rowspan="2"></th></tr>
<tr><th>MW</th></tr>
<tr><td>HE Pec Mlini</td><td>30</td><td>HROR</td><td>WAT</td><td>[41]</td></tr>
<tr><td>HE Trebinje 2</td><td>8</td><td>HDAM</td><td>WAT</td><td>[46]</td></tr>
<tr><td>HE Bogatici</td><td>7</td><td>HROR</td><td>WAT</td><td rowspan="3">[47]</td></tr>
<tr><td>HE Vlasenica</td><td>0,9</td><td>HROR</td><td>WAT</td></tr>
<tr><td>HE Mesica Nova</td><td>4,8975</td><td>HROR</td><td>WAT</td></tr>
<tr><td>HE Bistrica B-5 A</td><td>3,87</td><td>HROR</td><td>WAT</td><td>[48]</td></tr>
<tr><td>HE Majdan</td><td>2,635</td><td>HROR</td><td>WAT</td><td rowspan="4">[49]</td></tr>
<tr><td>HE Botun</td><td>1,043</td><td>HROR</td><td>WAT</td></tr>
<tr><td>HE Jezernica</td><td>1,294</td><td>HROR</td><td>WAT</td></tr>
<tr><td>HE Mujakovici</td><td>1,536</td><td>HROR</td><td>WAT</td></tr>
<tr><td>HE Modrac</td><td>1,898</td><td>HROR</td><td>WAT</td><td>[50]</td></tr>
<tr><td>HE Tresanica T-4</td><td>1,23</td><td>HROR</td><td>WAT</td><td>[51]</td></tr>
<tr><td>HE Osanica</td><td>1,084</td><td>HROR</td><td>WAT</td><td>[52]</td></tr>
<tr><td>HE Novakovici</td><td>5,77</td><td>HROR</td><td>WAT</td><td>[53]</td></tr>
<tr><td>HE Una Kostela</td><td>9,4</td><td>HROR</td><td>WAT</td><td>[54]</td></tr>
</table>

4.5.2.2. Thermal power plants

There are four thermal power plants in Bosnia and Herzegovina. All of them are coal-fired. TE Tuzla is the largest one with total installed capacity of 630 MW. The smallest among them is TE Gacko with 255 MW of installed capacity. Power plant flexibility data are calculated according to some scientific publications and are presented in Table 20[24]. In addition to this, data related to the costs of running and operating units is also covered by the same publications.Highest maximal efficiency has TE Gacko and it amounts to 34,15%, minimal efficiency is equal to all coal-fired power plants and amounts to 29%, ramp up and ramp down rate are also equal for all coal-fired power plants and amount to 2,5% of nominal power per minute. TE Tuzla has lowest minimal partial load and it amounts to 8,722%. The CO_2 intensity is also equal for all coal-fired power plants and it is equal to 1.062 kg/MW. [24]

Table 20 Technology related data for thermal power plants in Bosnia and Herzegovina

		Unit			
Variable		TE Tuzla	TE Kakanj	TE Ugljevik	TE Gacko
Efficiency	**%**	34	34	34,1	34,15
Min Up Time	**h**	6	6	6	6
Min Down Time	**h**	1,5	1,5	1,5	1,5
Ramp Up Rate	**%/min**	2,5	2,5	2,5	2,5
Ramp Down Rate	**%/min**	2,5	2,5	2,5	2,5
Min Part Load	**%**	8,722	12,636	35	35
Min Efficiency	**%**	29	29	29	29
Start Up Time	**h**	6	6	6	6
CO2 Intensity	**kg/MW**	1.061	1.062	1.062	1.062

Table 21 shows cost related data of thermal power plants in Bosnia and Herzegovina from where it is clear that TE Tuzla has the higest start up cost of 45.832 EUR, mainly because it is the largest power plant. TE Gacko has minimal start up costs with value of 20.245 EUR because this is power plant with lowest installed capacity.

Table 21 Cost related data of thermal power plants in Bosnia and Herzegovina

		Unit			
Variable		TE Tuzla	TE Kakanj	TE Ugljevik	TE Gacko
Start Up Cost	**€**	45.832	35.083	26.452	25.723
No Load Cost	**€**	0	0	0	0
Ramping Cost	**€**	1.8	1,8	1,8	1,8

According to various different sources, planed outages due to maintenance were scheduled for TE Tuzla [56], TE Kakanj [57], TE Ugljevik [58] and TE Gacko [59]. Hourly values of outage factor for thermal power plants in Serbia are determined according to (16) and graphical representation of outages are presented in Figure 15. Planed outages were scheduled in the way that there were never two power plants of the grid at the same time. When overhaul is finished in one unit, within few days, start overhaul of second unit. During this period thermal power plants were not able to produce electricity. Electricity production of thermal power plants in 2010 was 7683 GWh or 49,4% of total electricity production, of witch TE Tuzla produced 3011,1 GWh or 19,36% of total production, TE Kakanj produced 1815,9 GWh or 11,68% of total production, TE Gacko produced 1540,3 GWh or 9,9% of total production and TE Ugljevik produced 1315,7 GWh or 8,46% of total production[34].

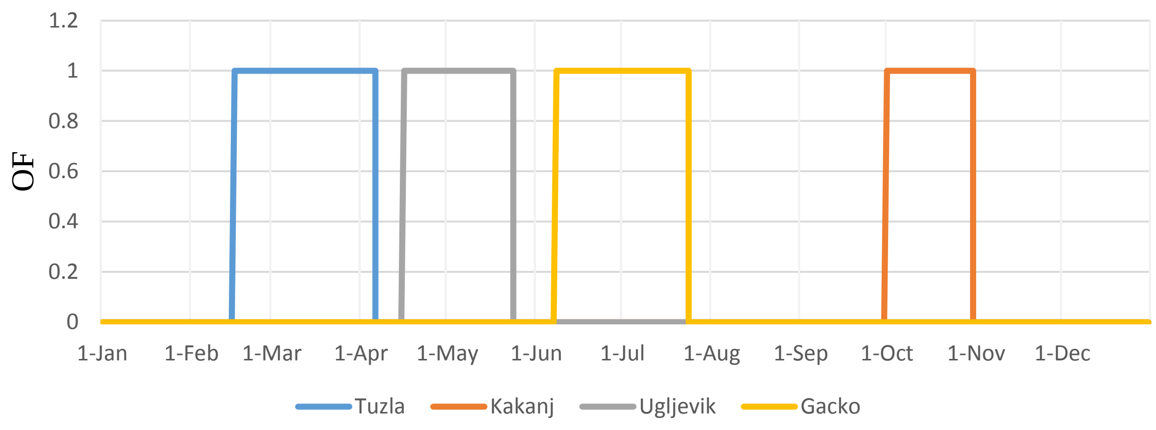

Figure 15 Hourly values of outage factor for thermal power plants in Bosnia and Herzegovina

4.5.2.3. Hydropower plants

There are eleven accumulation hydropower plants in Bosnia and Herzegovina. The largest one is RHE Capljina located on the river Neretva, with total installed capacity of 420 MW and smalles one is HE Trebinje 2 located on river Trebisnjica, with total installed capacity of 8 MW. RHE Capljina is also the only pumped hydro storage unit in Bosnia and Herzegovina. Technology related data for hydropower plants are determined from various sources and calculated where not available.[24] Table 22 represents technology related data for hydropower plants where one example of accumulation hydropower plant, and one example of run-of-river hydropower plant is presented. All remaining hydropower plants have technology related data according to the units HE Jablanica and HE Grabovica. It can be seen that minimal efficiency of all hydropower plants amounts to 50%, start up time is one hour and they have no CO_2 intensity.

Table 22 Technology related data for hydropower plants in Bosnia and Herzegovina

Variable		**Unit**	
		HE Jablanica	HE Grabovica
Min Up Time	**h**	-	-
Min Down Time	**h**	-	-
Ramp Up Rate	**%/min**	1	1
Ramp Down Rate	**%/min**	1	1
Min Part Load	**%**	-	-
Min Efficiency	**%**	50	50
Start Up Time	**h**	1	1
CO2 Intensity	**kg/MW**	-	-

Efficiency values are shown in Table 23. Efficiency of each hydropower plant is determined according to equation (11), from where it is clear that HE Jablanica has the best efficiency of 94,38% while HE Jajce 2 has the worst one of 78,21%. Efficiency of small run-of-river hydropower amounted to 85% due to lack of data for determination.

Table 23 Efficiency values for hydropower plants in Bosnia and Herzegovina

Unit	**Efficiency**	**Unit**	**Efficiency**
	%		**%**
HE Trebinje 1	78,7918	HE Trebinje 2	82,.3743
HE Grabovica	89,9448	HE Bogatici	85
RHE Capljina	83,567	HE Novakovici	85
HE Visegrad	93,3433	HE Mesica Nova	85
HE Salakovac	94,386	HE Bistrica B-5 A	85
HE Jablanica	94,3061	HE Majdan	85
HE Rama	89,4185	HE Botun	85
HE Bocac	85,1646	HE Modrac	85
HE Dubrovnik	89,9442	HE Mujakovici	85
HE Mostar	84,9474	HE Jezernica	85
HE Mostarsko Blato	93,8645	HE Tresanica T-4	85
HE Jajce 1	83,8246	HE Osanica	85
HE Jajce 2	78,2084	HE Vlasenica	85
HE Pec Mlini	90,4135	HE Una Kostela	90,7391

Electricity production of hydropower plants and its share in total electricity production in 2010 is presented in Table 24. Total electricity production of hydropower plants in 2010 was 7.870,4 GWh or 50,6% of total electricity production. Higest producton was in HE Visegrad with the value of 1283 GWh or 24,17% of total electricity production. The run-of-river hydropower plants produced 1643,2 GWh or 30,96% of total electricity production.

Table 24 Electricity production of hydropower plants in Bosnia and Herzegovina[34]

Unit	**2010**		**Unit**	**2010**	
	GWh	**%**		**GWh**	**%**
HE Jablanica	1.004,1	18,92	HE Bocac	882,9	16,63
HE Grabovica	407,3	7,67	HE Rama	320,3	6,03
HE Salakovac	668,2	12,59	HE Mostar	321,7	6,06
HE Visegrad	1.283	24,17	HE Jajce 1	78,9	1,49
HE Trebinje 1	794,1	14,96	HE Jajce 2	794,2	14,96
HE Trebinje 2	797	15,02	PHE Capljina	123,7	2,33
HE Dubrovnik (G2)	353,9	6,67	HE Pec-Mlini	41,1	0,77

Technical data related to the power plants are presented in Table 25. From there it is clear that HE Dubrovnik has largest accumulation with volume of 1.110.000.000 m^3 and HE Trebinje 2 have smallest accumulation with volume of 9.600.000 m^3. HE Visegrad have highest installed flow with small net head while HE Dubrovnik have high nominal head and low installed flow.

Table 25 Technical data of hydropower plants in Bosnia and Herzegovina

Unit	Nominal power	Installed flow	Net head	Accumulation volume	Energy in accumulation	
	MW	m^3/s	m	m^3	MWh	
HE Trebinje 1	168	210	103,5	1.070.000.000	1.010.700	[37]
HE Grabovica	114	380	34			[38]
HE Salakovac	210	540	42	68.000.000	7.782,6	
HE Jablanica	181	208,8	93,7	288.000.000	73.535,76	
RHE Capljina	420	225	227,7	6.500.000	3.400	[39]
HE Visegrad	315	800	43	161.000.000	18.865,2	[40]
HE Rama	160	64	285	466.000.000	303.000	[41]
HE Bocac	110	240	54,86	42.900.000	5.322	[42]
HE Dubrovnik	108	45	272	1.110.000.000	821.990,8	[43]
HE Mostar	72	360	24	10.920.000	714,168	[44]
HE Mostarsko Blato	60	36	181			
HE Jajce 1	60	74	98,6			[45]
HE Jajce 2	30	79,8	49			
HE Pec Mlini	30,6	30	115			[41]
HE Trebinje 2	8	45	22	9.600.000	6.037	[46]
HE Bogatici	9,4	88				[47]
HE Vlasenica	1,084	1,75				
HE Mesica Nova	5,77	5				
HE Bistrica B-5 A	4,8975	8				[48]
HE Majdan	3,87	2				[49]
HE Botun	2,635	1,6				
HE Jezernica	1,536	0,94				
HE Mujakovici	1,898	15				
HE Modrac	1,043	1,13				[50]
HE Tresanica T-4	1,294	0,45				[51]
HE Osanica	1,23	1,35				[52]
HE Novakovici	7	5,5				[53]
HE Una Kostela	0,9	0,7				[54]

The AF for run-of-river hydropower plants has been calculated according to equation (1). The graphical presentation of AF's for HE Jajce 1 and HE Grabovica are illustrated in Figure 16. The AF (blue line) represents hourly values of all run-of-river hydropower plants, and AFs for HE Jajce 1 and HE Grabovica are illustrated to show how production trend looks like for each unit. It is clear that from November till May run-of-river hydropower plants operate at higher capacity because of the high river discharge rates. From May till November there are some oscilations caused by low inflows due to low percitipations during summer.

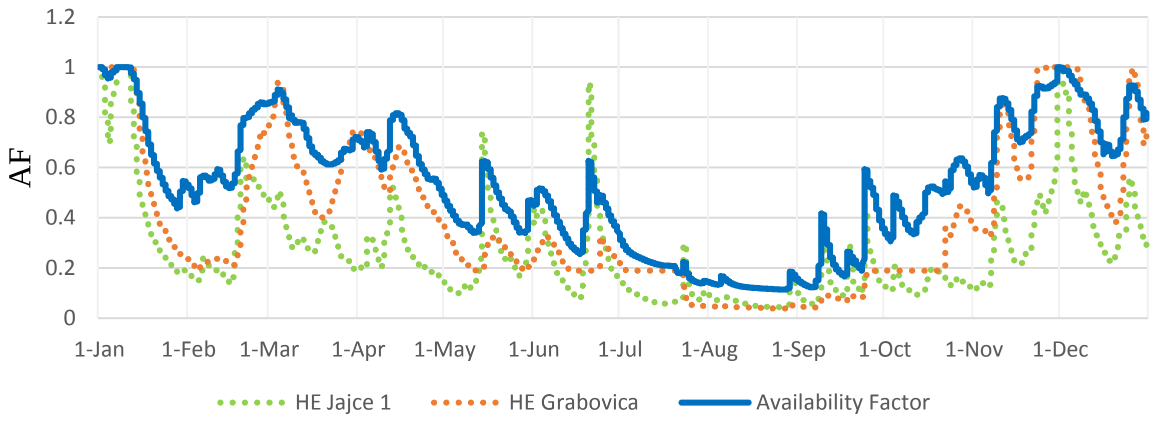

Figure 16 Hourly values of availability factor for run-of-river hydropower plants in Bosnia and Herzegovina

RL for each accumulation hydropower plant in Bosnia and Herzegovina is determined according to (6). RLs are divided by the accumulation capacity. Hydropower plants with large accumulations are shown in Figure 17. From there it can be seen that HE Jablanica has similar accumulation levels to HE Rama and HE Dubrovnik has similar accumulation levels to the HE Trebinje 1. The main reason for that is the combination of similar river hydrologies and electricity production. The RL of HE Dubrovnik and HE Trebinje 1 shows less fluctuating trend because of its large accumulation in relation to its power capacity. All of them reach minimum accumulation levels between September and December mainly due to the low inflows and relatively high electricity demand during the autumn. HE Jablanica also reaches minimum accumulation level in period between March and May due to high electricity demand during the winter.

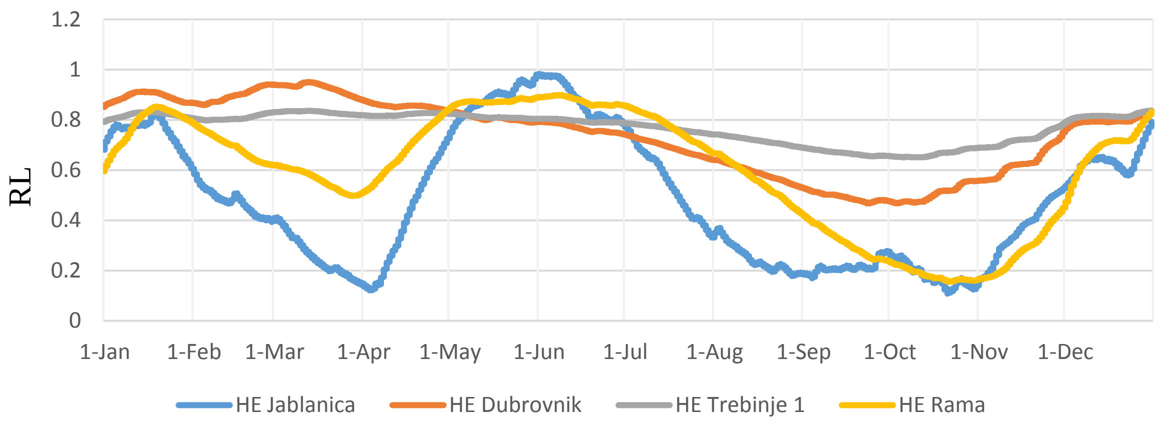

Figure 17 Hourly values of reservoir level for hydropower plants with large accumulation in Bosnia and Herzegovina

Reservoir level of hydropower plants with smaller accumulation capacity is illustrated in Figure 18, from where it can be seen how reservoir level of hydropower plants with smaller accumulation differ substantially from those with larger accumulations. Reason of high fluctuating trend lies is the small size of the accumulation, so when the hydropower plant works at its nominal power it drains water from the storage within few hours or days. These types of hydropower plants are often used for meeting peeks in electricity demand.

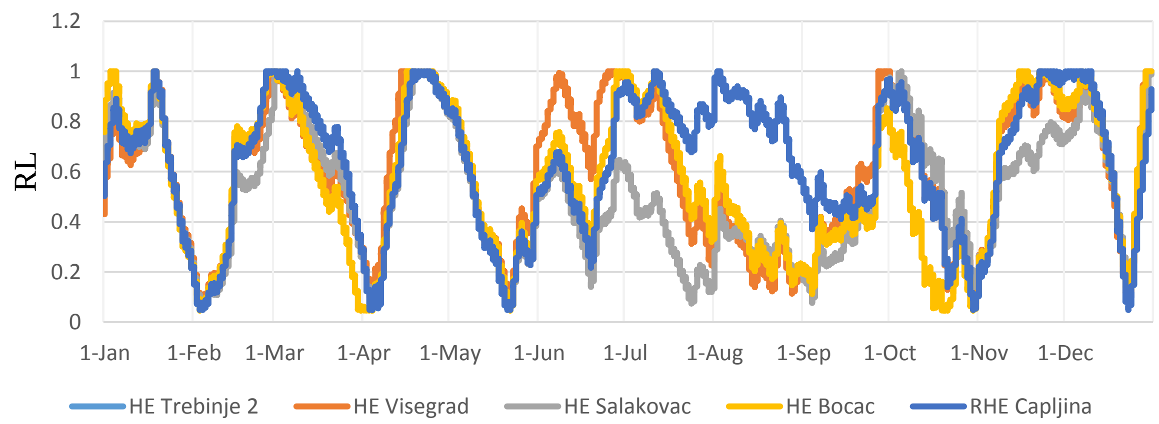

Figure 18 Hourly values of reservoir level for hydropower plants with small accumulation in Bosnia and Herzegovina

Scaled inflows have been calculated for accumulation hydropower plants according to equation (15) and they are divided by the type of inflows that is used for each hydropower plant. Hydropower plants with inflows that look like the ones from the Figure 2, are presented in Figure 19. Scaled inflows are in direct correlation with river discharge rates. Because of that, higher values usually occure during spring and winter months, especially during December where their values are often higher than 1. The lowest values of scaled inflows usually occure from June to October, when river discharge rates are the lowest. Each hydropower plant have different value of scaled inflow because of different river hydrology.

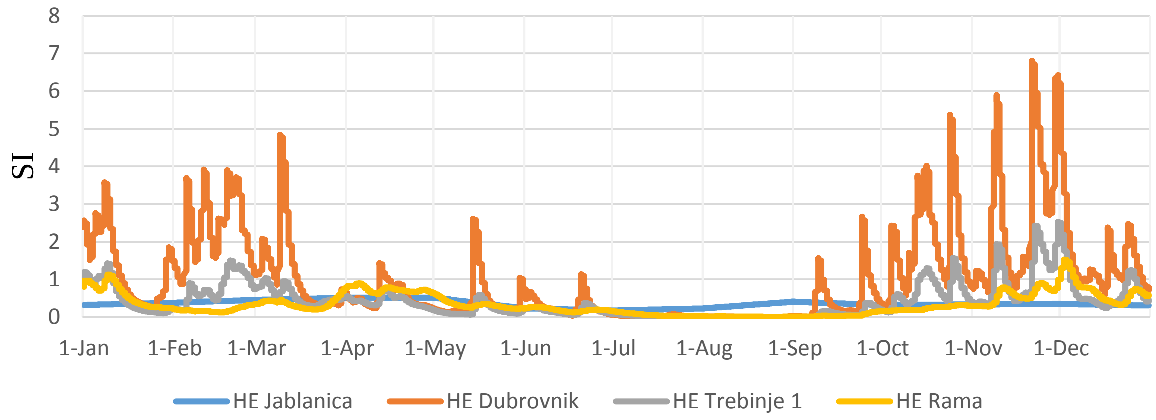

Figure 19 Hourly values of scaled inflows for hydropower plants in Bosnia and Herzegovina

Scaled inflows of hydropower plants that uses modified distribution of inflows are illustrated in Figure 20. And in this case scaled inflows are in direct correlation with river discharge rates. Because of that, higher values usually occure during the spring and winter months, especially during the December where their values are often higher than 1. The lowest values of scaled inflows usually occure from June to October, when river discharge rates are the lowest. The Drop that occurs for RHE Capljina beetween July and September is due to extremely low percitipation.

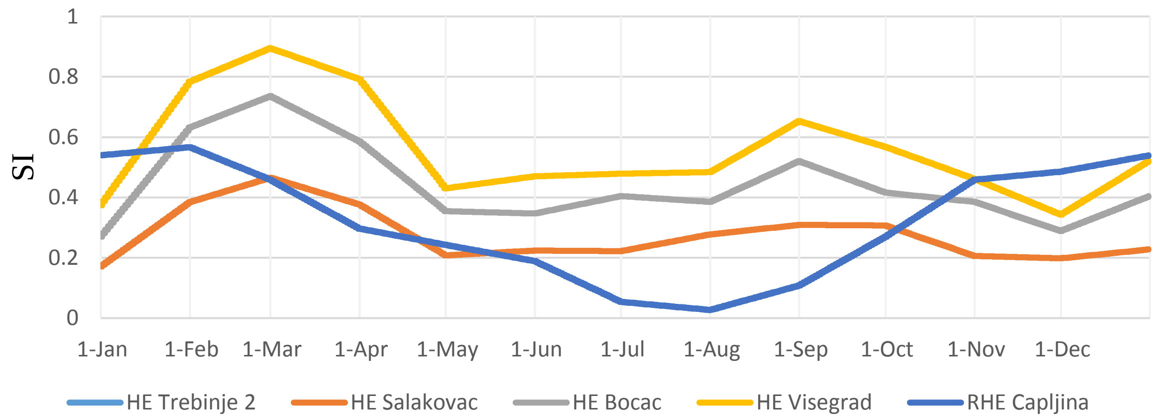

Figure 20 Hourly values of scaled inflows for hydropower plants in Bosnia and Herzegovina that uses modified hourly river flow distribution

4.5.2.4. Alternative scenarios

This section describes new production capacities installed in 2020 and 2030 according to cases A, B and C [60]. In addition to the list of power plants presented in Table 12, in Table 26 are new capacities of power plants in 2020 presented. They are added to existing ones from the Reference scenario. New capacities in 2030 are presented in Table 27 Simmilar as before they are also added to the existing ones from the reference scenario. Case C has no new thermal power plants because it is high RES scenario. Instaled capacities of wind and solar power plants are increasing in future. All technology and cost related data for new power plants are determined according to some scientific publications and imported into model [25][24].

Table 26 New capacities of Bosnia and Herzegovina in 2020

	Case A and B	case C
	MW	MW
Hydropower plants	554	1.258
Thermal power plants	2.270	0
Solar power plants	-	121,84
Wind power plants	564	1.593,04
Total	4.092	6.742

Table 27 New capacities of Bosnia and Herzegovina in 2030

	Case A and B	case C
	MW	MW
Hydropower plants	1.258	1.285
Thermal power plants	3.720	-
Solar power plants	-	1.593
Wind power plants	564	1.593
Total	5.542	4.471

Availability factor of hydropower plants in 2010 is applied to new hydropower plants in 2020 and 2030. New thermal power plants are TE Tuzla B with 500 MW of installed power, TE Bugojno with 300 MW of installed power and TE Kongora with 550 MW of installed power.

Availability factor for solar power plants is illustrated in Figure 21. Hourly values of power output for solar power plants are obtained from Renewable ninja and corrected using values of global irradiation from pvgis [29][30]. Corected values of hourly power output for solar power plants are representing availability factors and are used in 2020 and 2030 in all three cases. The electricity production of solar power plant is oscilating on daily basis because solar power plants are producing electricity only during the day. Highest electricity production is achived in spring because in that period there are lot of sunny days. Low production with high oscilations are in winter because days are cloudy with often precipitations.

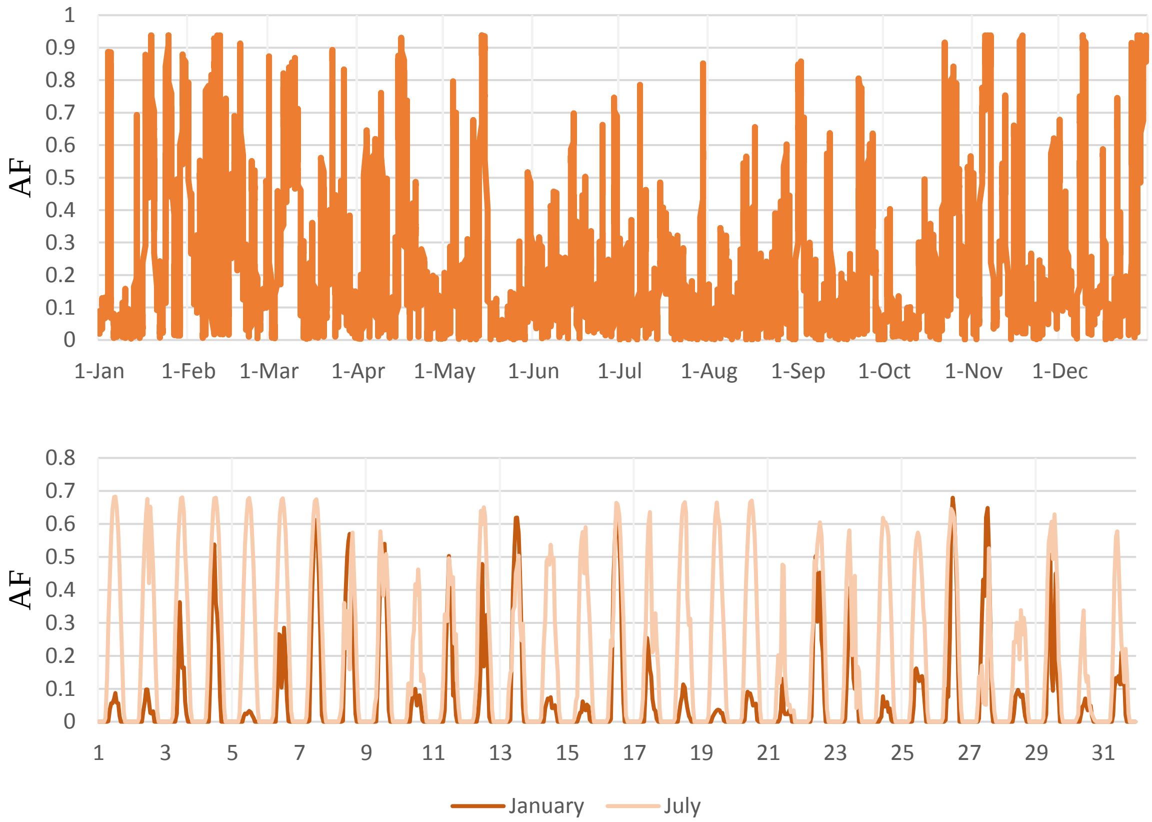

Figure 21 Hourly values of availability factor for solar power plants in Bosnia and Herzegovina

Availability factor for wind power plants can be seen in Figure 22. Horly values of power output for wind power plants are obtained from Renewables ninja and they represent availability factor used in 2020 and 2030 for all three scenarios[29]. It is clear that from mid-May til September wind power plants operate at lower values due to lack of wind during summer. During the whole year there are oscilations in power production from wind turbine because of stohactic nature of wind.

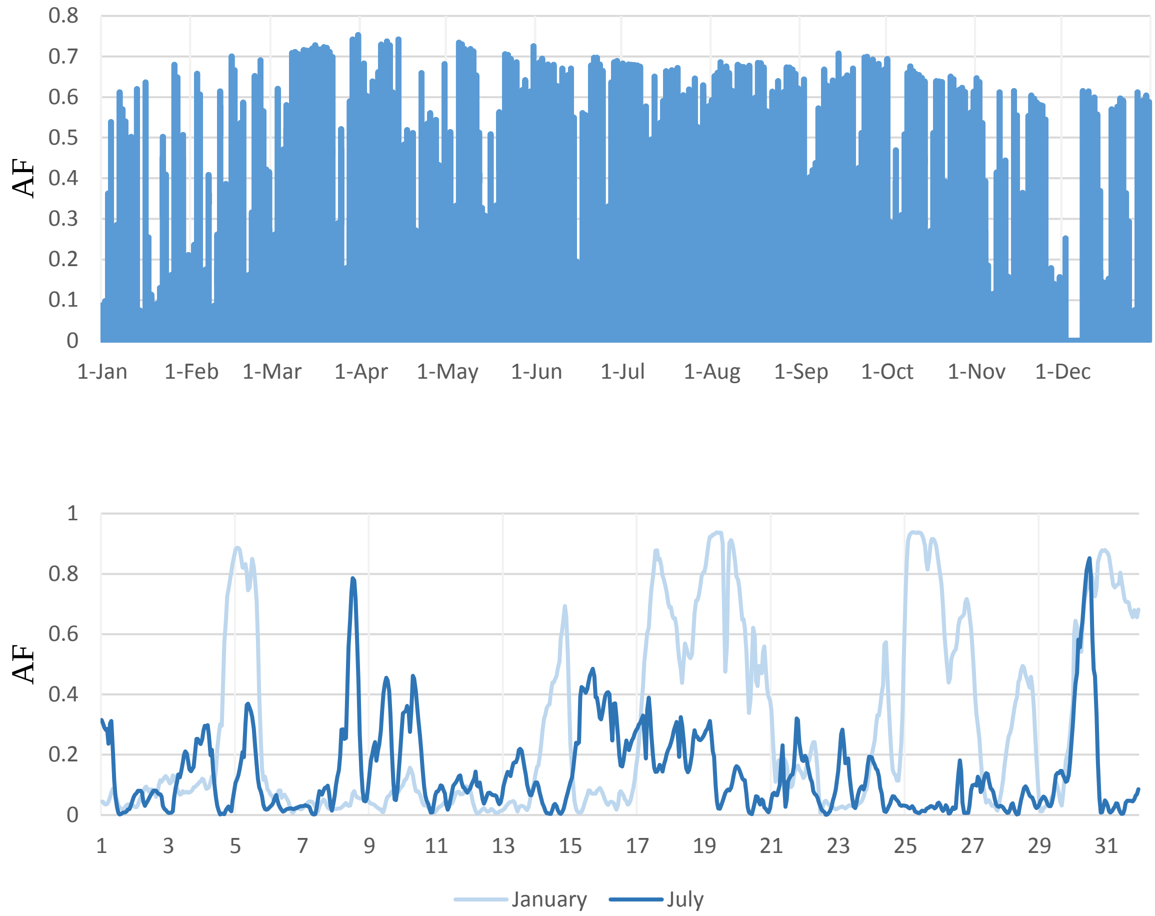

Figure 22 Hourly values of availability factor for wind power plants in Bosnia and Herzegovina

4.6. Serbia

The capital and at the same time the largest city of Serbia is Belgrade. According to national census population in 2010 is 9.059.046[19]. Serbia have borders with Croatia, Bosnia and Herzegovina, Kosovo, Montenegro, Romania, Hungary, Macedonia and Bulgaria. Transmission network of Serbia as well as position of larger power plants and substations in 2010 can be seen in Figure 23. Relatively uniform electricity demand is established during the whole year. The year 2010 is year with high percitipations which have great influence on electricity production from hydropower plants. Several large substations have been located all over the country. It can be seen that Serbia have 400 kV transmission system within its neighbouring countries Croatia, Bosnia and Herzegovina, Romania and Bulgaria. With

Montenegro, Serbia is connected through 220 kV transmission network and Serbia had no connection with Macedonia in 2010.

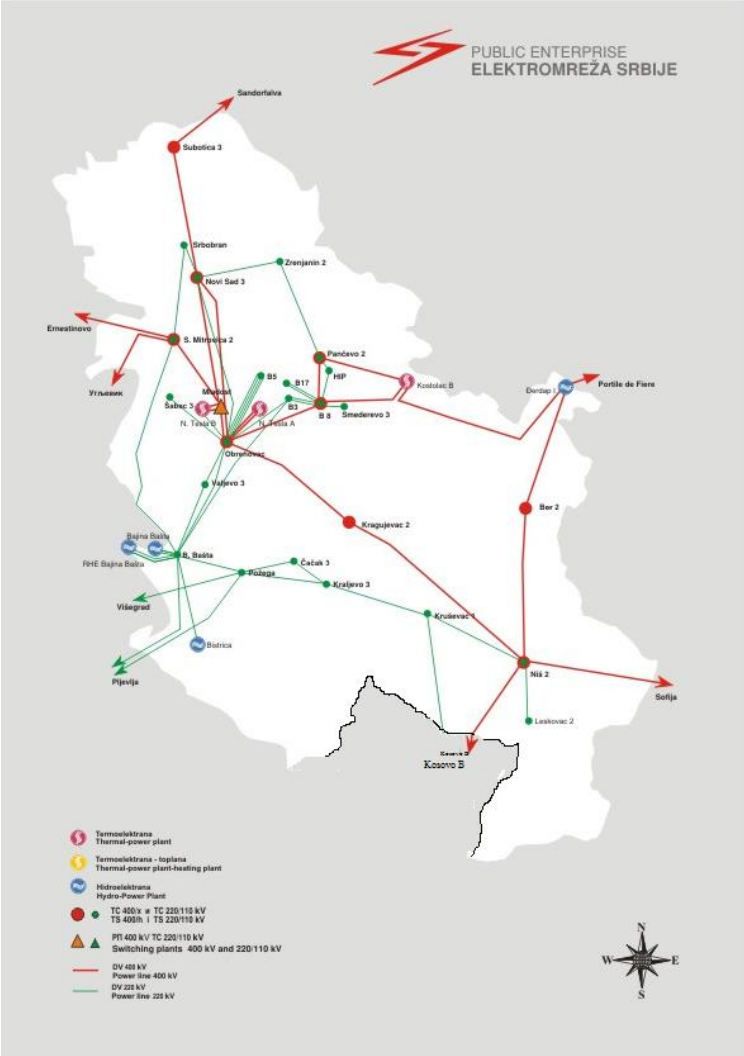

Figure 23 Transmission network of Serbia and position of larger power plants [61]

4.6.1. Electricity demand

4.6.1.1. Reference scenario

The electricity demand of Serbia is presented in Figure 24. Overall annual electricity consumption of Serbia in year 2010 amounted to 34.444,57 GWh[18]. During the winter months it is slightly higher than in summer due to the fact that almost 24% of population is using electricity for space heating [62]. Highest demand of 6.601,2 MW has been recorded during December while the lowest is 2.104 MW and recorded in May. Electricity demand vary between 2.000 MW and 6.000 MW with average value of 3.932 MW.

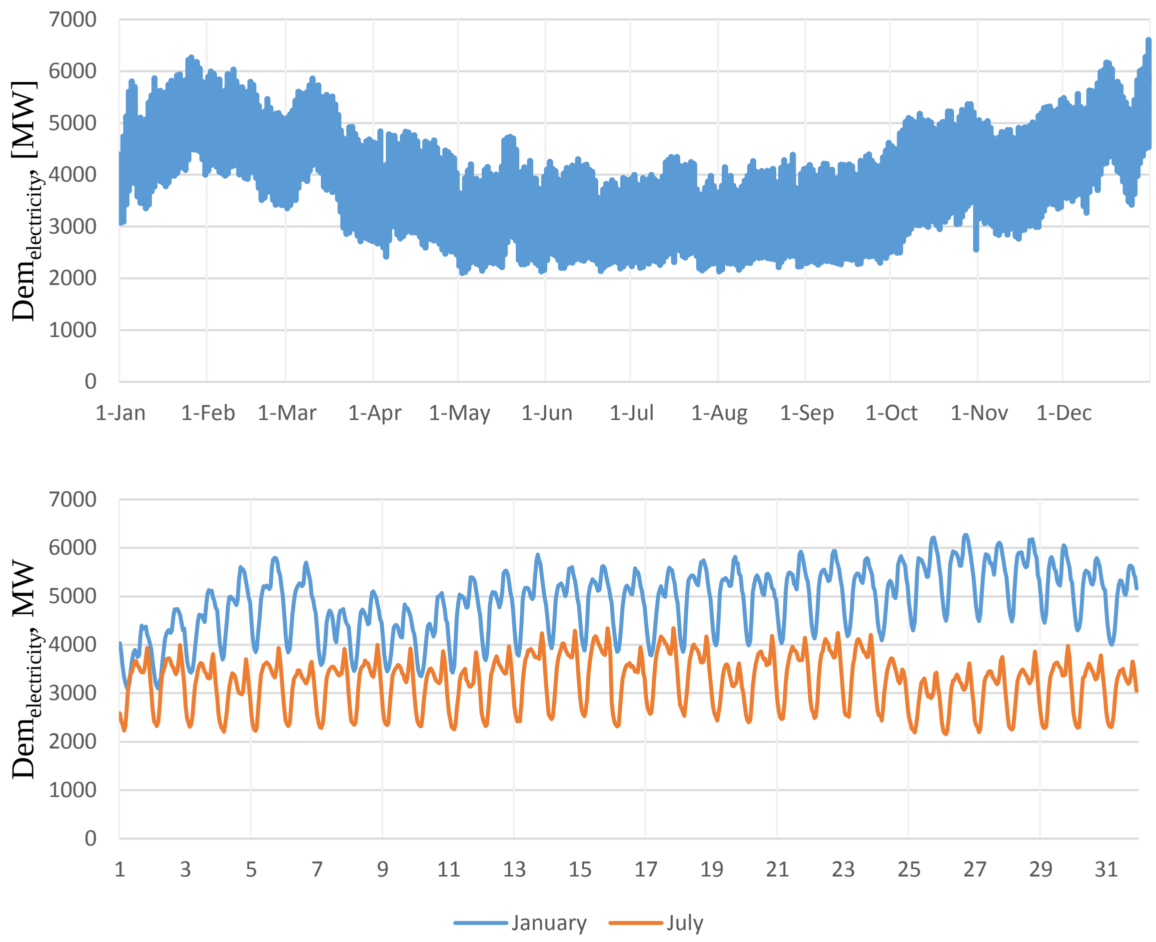

Figure 24 Hourly values of electricity demand of Serbia

4.6.1.2. Alternative scenarios

According to demand forecasts for the year 2020 and 2030 electricity demand in Bosnia and Herzegovina should be 37.060 GWh and 37.550 GWh respectivley [20]. The hourly values of electricity demand presented in Figure 24 are scaled and used in all three scenarios whitihin a specific year. From there it is clear that demand in Bosnia and Herzegovina is increasing from 2010 to 2030.

4.6.2. Electricity production

4.6.2.1. Reference scenario

The electricity production in Serbia in 2010 consist of electricity produced by thermal power plants and hydropower plants. A list of electricity generating units can be seen in Table 28. The total installed capacity in 2010. was 7.136,6 MW of witch 3.936 MW are coal fired thermal power plans, 353 MW are gas fired thermal power plants, 2.728,6 MW are accumulation hydropower plants, and 119 MW are run-of-river hydropower plants. Installed capacities in 2010 are sufficient to cover peak loads because highest electricity demand is 6.601,2 MW and total installed capacity is 7.136,6 MW which is higher then maximal demand by 535,4 MW. Highest share of total installed capacities have coal-fired thermal power plants and it amounts to 55,15%, followed by accumulation hydropower plants with 38,23%. Gas fired thermal power plants accounted for 4,95% of total installed capacities and run-of-river power plants have lowest share of 1,67%. TE Nikola Tesla A is largest power plant in Serbia with installed power of 1502 MW or 21,05% of total installed capacity.

Table 28 List of power plants in Serbia

Unit	Power Capacity MW	Technology	Fuel	
TE Kolubara G5	245	STUR	LIG	[63]
TE Kostolac A	281	STUR	LIG	
TE Kostolac B	640	STUR	LIG	
TE Morava G1	108	STUR	LIG	
TE Nikola Tesla A	1.502	STUR	LIG	
TE Nikola Tesla B	1.160	STUR	LIG	
TETO Novi Sad	208	COMC	GAS	
TETO Zrenjanin	100	COMC	GAS	
TETO Sremska Mitrovica	45	COMC	GAS	
HE Bajina Basta G4	364	HDAM	WAT	[64]
HE Pirot	80	HDAM	WAT	[65]
HE Derdap 2	270	HDAM	WAT	[66]
HE Derdap 1	1.058	HDAM	WAT	[67]
HE Bistrica	102	HDAM	WAT	[68]
HE Kokin Brod	22	HDAM	WAT	[69]
HE Potpec	54	HDAM	WAT	[70]
HE Uvac	36	HDAM	WAT	[71]
HE Vrla 1-4	128.6	HDAM	WAT	[72]
RHE Bajina Basta G2	614	HPHS	WAT	[73]
HE Seljasnica	0.9	HROR	WAT	[74]
HE Sicevo	1.34	HROR	WAT	[75]
HE Sokolovica	5.2	HROR	WAT	
HE Vlasontice	1.5	HROR	WAT	
HE Ostrovica	1.05	HROR	WAT	
HE Zvornik	96	HROR	WAT	[76]
HE Medjuvrsje	7	HROR	WAT	[77]
HE Ovčar Banja	6	HROR	WAT	

4.6.2.2. Thermal power plants

There are nine thermal power plants in Serbia. Six of them are coal fired and three of them are gas fired. TE Nikola Tesla A is the largest one with total installed capacity of 1502 MW. The smallest among them is TETO Sremska Mitrovica with 45 MW of installed capacity. Power plant flexibility data are calculated according to some scientific publication and are presented in Table 29[24]. In addition to this, data related to the costs of running and operating units is also covered by the same publications[25]. Highest maximal efficiency has TE Kolubara and TE Morava and it amounts to 34,15%, minimal efficiency is equal to all coal-fired power plants and amounts to 29%, ramp up and ramp down rate are also equal for all coal-fired power plants and amounts to 2,5% of nominal power per minute. The CO_2 intensity is also equal for all coal-fired power plants and it amounts to 1.062 kg/MW [24].

Table 29 Technology related data for coal thermal power plants in Serbia

Variable		**Unit**				
		TE Kolubara	TE Kostolac A	TE Kostolac B	TE Morava	TE Nikola Tesla A/B
Efficiency	**%**	34,15	34,1	34	34,15	34
Min Up Time	**h**	6	6	6	6	6
Min Down Time	**h**	1,5	1,5	1,5	1,5	1,5
Ramp Up Rate	**%/min**	2,5	2,5	2,5	2,5	2,5
Ramp Down Rate	**%/min**	2,5	2,5	2,5	2,5	2,5
Min Part Load	**%**	35	35	35	35	35
Min Efficiency	**%**	29	29	29	29	29
Start Up Time	**h**	6	6	6	6	6
CO2 Intensity	**kg/MW**	1.062	1.062	1.062	1.062	1.062

Table 30 shows cost related data of coal-fired thermal power plants in Serbia from where it is clear that TE Nikola Tesla A has the highest start up cost with value of 67.590 EUR, mainly because it is largest power plant. TE Morava has minimal start up costs with value of 20.245 EUR because this is power plant with lower installed capacity.

Table 30 Cost related data of coal thermal power plants in Serbia

Variable		Unit				
		TE Kolubara	TE Kostolac A/B	TE Morava	TE Nikola Tesla A	TE Nikola Tesla B
Start Up Cost	**€**	24.898	26.120/38.313	20.245	67.590	55.974
Ramping Cost	**€**	1,8	1,8	1,8	1,8	1,8

Technology related data for gas-fired thermal power plants are presented in Table 31. The gas-fired power plants have maximal efficiency of 57%, minimal efficiency accounts for 49%, ramp up and ramp down rate are also equal for all coal-fired power plants and amounts to 6,415% of nominal power per minute. The CO_2 intensity for all gas-fired power plants is 398 kg/MW.[24]

Table 31 Technology related data for gas thermal power plants in Serbia

Variable		Unit		
		TETO Novi Sad	TETO Zrenjanin	TETO Sremska Mitrovica
Efficiency	**%**	57	57	57
Min Up Time	**h**	2	2	2
Min Down Time	**h**	3,25	3,25	3,25
Ramp Up Rate	**%P/min**	6,415	6,145	6,145
Ramp Down Rate	**%P/min**	6,415	6,145	6,145
Min Part Load	**%**	18,51	40	50
Min Efficiency	**%**	49	49	49
Start Up Time	**h**	3	3	3
CO2 Intensity	**kg/MW**	398	398	398

Table 32 shows cost related data for gas-fired thermal power plants in Serbia from where it is clear that TETO Novi Sad has the highest start up cost of 12.480 EUR, mainly because it is largest gas-powered power plant. TETO Srijemska Mitrovica has minimul start up cost with value of 2.700 EUR because this power plant has the lowest installed capacity.

Table 32 Cost related data of gas thermal power plants in Serbia

Variable		**Unit**		
		TETO Novi Sad	TETO Zrenjanin	TETO Sremska Mitrovica
Start Up Cost	**€**	12.480	6.000	2.700
No Load Cost	**€**	0	0	0
Ramping Cost	**€**	0,375	0,375	0,375

According to various diferent sources planed outages due to maintenance were scheduled for TE Kostolac A, TE Kostolac B, TE Nikola Tesla A, Nikola Tesla B, TE Kolubara and TE Morava[78][79]. Hourly values of outage factor for thermal power plants in Serbia are determined according to (16) and graphical representation of outages are presented in Figure 25, from where it can be seen that some units produce electricity during planed outages. This is applied to power plants with multiple blocks and when repairs are conducted in one block, other blocks are operating. Electricity production of thermal power plants in 2010 was 23.162 GWh or 64,6% of total electricity production, of witch TE Nikola Tesla A produced 8.581 GWh or 23,93% of total production, TE Nikola Tesla B produced 8.113 GWh or 22,63% of total production, TE Kostolac B produced 2.921 GWh or 8,15% of total production, TE Kostolac A produced 1.888 GWh or 5,27% of total production, TE Kolubara produced 1.081 GWh or 3,01% of total production and TE Morava produced 578 GWh or 1,61% of total production[63].

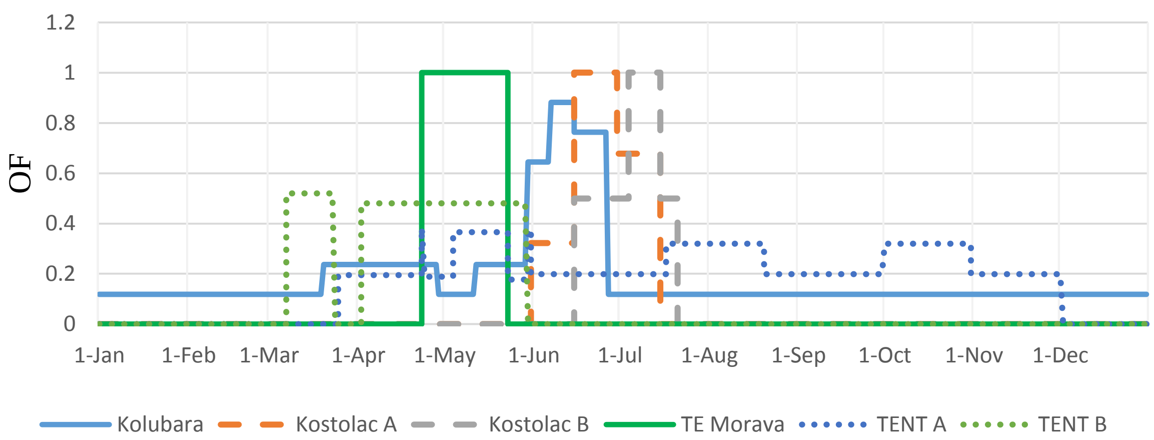

Figure 25 Hourly values of outage factor for thermal power plants in Serbia

4.6.2.3. Hydropower plants

There are ten accumulation hydropower plants in Serbia. The largest one is HE Derdap 1 located on the river Dunav, with total installed capacity of 1058 MW and smalles one is HE Kokin Brod located on river Uvac, with total installed capacity of 22 MW. There is also one pumped hydro storage unit, RHE Bajina Basta located on the river Drina with total installed capacity of 614 MW. The total installed capacity of all small run-of-river hydropower plants is 119 MW. Technology related data for hydropower plants are determined from various sources and calculated where not available[24]. Table 33 represents technology related data for hydropower plants where one example of accumulation hydropower plant, and one example of run-of-river hydropower plant is presented. All remaining hydropower plants have technology related data according to the units HE Bistrica and HE Zvornik. It can be seen that minimal efficiency of all hydropower plants amounts to 50%, start up time is one hour and they have no CO_2 intensity.

Table 33 Technology related data for hydropower plants in Serbia

		Unit	
Variable		HE Bistrica	HE Zvornik
Min Up Time	**h**	-	-
Min Down Time	**h**	-	-
Ramp Up Rate	**%/min**	1	1
Ramp Down Rate	**%/min**	1	1
Min Part Load	**%**	-	-
Min Efficiency	**%**	50	50
Start Up Time	**h**	1	1
CO2 Intensity	**kg/MW**	-	-

Efficiency values are shown in Table 34. The Efficiency of each hydropower plant is determined according to equation (11), from where it is clear that RHE Bajina Basta has the best efficiency of 89,6% while HE Zvornik has the worst one of 69,5%. Efficiency of small run-of-river hydropower amounted to 100% due to lack of data for determination

Table 34 Efficiency values for hydropower plants in Serbia

Unit	Efficiency	Unit	Efficiency
	%		%
HE Zvornik	0.69532	HE Potpec	0.86878
HE Medjuvrsje	0.85324	HE Uvac	0.85343
HE Ovčar Banja	0.82756	HE Vrla 1-4	0.83398
HE Bajina Basta G4	0.81242	RHE Bajina Basta G2	0.89561
HE Pirot	0.74577	HE Seljasnica	1
HE Derdap 2	0.72811	HE Sicevo	1
HE Derdap 1	0.82728	HE Sokolovica	1
HE Bistrica	0.76347	HE Vlasontice	1
HE Kokin Brod	0.83283	HE ostrovica	1

Electricity production of hydropower plants and its share in total electricity production in 2010 is presented in Table 35. Total electricity production of hydropower plants in 2010 was 12.471 GWh or 34,78% of total electricity production. The higest producton was in HE Djerdap 1 with the value of 6387 GWh or 17,8% of total electricity production. The Run-of-river hydropower plants produced 52 GWh or 0,14% of total electricity production.

Table 35 Electricity production of hydropower plants in 2010 [63]

Unit	2010		Unit	2010	
	GWh	**%**		**GWh**	**%**
HE Zvornik	575	1,6	HE Potpec	248	0,7
HE Medjuvrsje	71	0,2	HE Uvac	68	0,19
HE Ovčar Banja			HE Vrla 1-4	462	1,29
HE Bajina Basta G4	1.677	4,68	RHE Bajina Basta G2	680	1,9
HE Pirot	212	0,6	HE Seljasnica	52	0,14
HE Derdap 2	1.551	4,33	HE Sicevo		
HE Derdap 1	6.387	17,8	HE Sokolovica		
HE Bistrica	462	1,29	HE Vlasontice		
HE Kokin Brod	75	0,21	HE ostrovica		

Technical data related to the power plants are presented in Table 36. From there it is clear that HE Djerdap 1 has the largest accumulation with volume of 2.800.000.000 m^3 and HE Bistrica has the smallest accumulation with volume of 7.600.000 m^3. HE Djerdap 1 has the highest installed flow with small net head while HE Bistrica has high nominal head and low installed flow.

Table 36 Technical data of hydropower plants in Serbia

Unit	Nominal power	Installed flow	Net head	Accumulation volume	Energy in accumulation	
	MW	m^3/s	m	m^3	MWh	
HE Bajina Basta G4	364	692	66	218.000.000	30.000	[64]
HE Pirot	80	45	243	180.000.000	75.000	[65]
HE Derdap 2	270	4.200	9	717.000.000	17.572,16	[66]
HE Derdap 1	1.058	4.800	27,16	2.800.000.000	207.230,8	[67]
HE Bistrica	102	36	378,3	7.600.000	7.834,593	[68]
HE Kokin Brod	22	37,4	72	210.000.000	202.000	[69]
HE Potpec	54	165	38,4	25.000.000	2.616	[70]
HE Uvac	36	43	100	213.000.000	34.000	[71]
HE Vrla 1-4	50,66	18,32	338	165.000.000	198.000	[72]
RHE Bajina Basta G2	614	129,2	555	170.000.000	194.000	[73]
HE Seljasnica	0,9	0,75				[74]
HE Sicevo	1,34	12				[75]
HE Sokolovica	5,2	40				
HE Vlasontice	1,5	4				
HE Ostrovica	1,05	9				
HE Zvornik	96	620				[76]
HE Medjuvrsje	7	20				[77]
HE Ovčar Banja	6	20				

The availability factor for run-of-river hydropower plants has been calculated according to equation (1). The graphical presentation of AF's for HE Sokolovica and HE Zvornik are illustrated in Figure 26. AF (blue line) represents hourly values of all run-of-river hydropower plants, and availability factors for HE Sokolovica and HE Zvornik are illustrated to show how production trend looks like for each unit. It is clear that from November til May run-of-river hydropower plants operate at full capacity because of the high river discharge rates. From May til November there are some oscilations caused by low inflows due to low percitipations during summer.

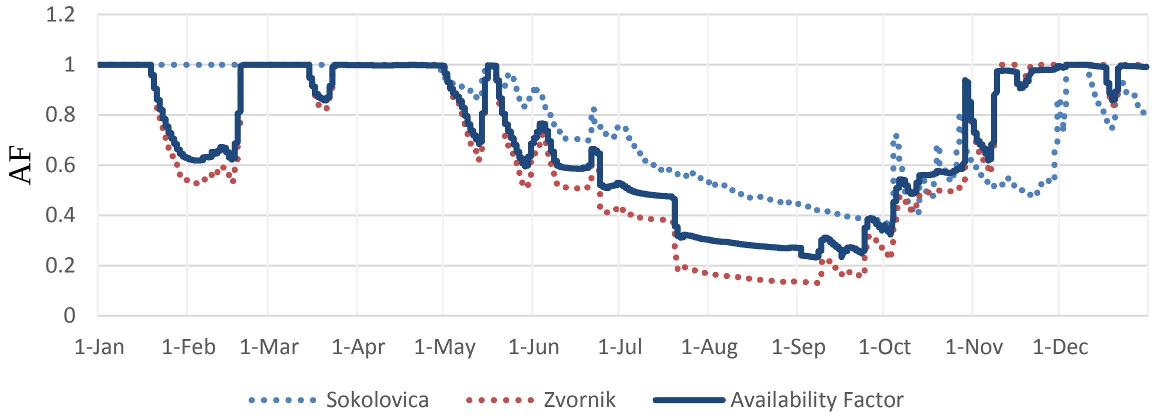

Figure 26 Hourly values of availability factor for run-of-river hydropower plants in Serbia

Reservoir level for each accumulation hydropower plant in Serbia is determined according to (6). Reservoir levels are divided by the accumulation capacity. Hydropower plants with large accumulation are shown in Figure 27. From there it can be seen that HE Vrla, HE Uvac and HE Bajina Basta G2 have similar accumulation levels throughout the year. The main reason for that is the combination of similar river hydrologies and electricity production. Reservoir level of HE Kokin Brod shows less fluctuating trend because of its large accumulation in relation to its power capacity. All of them reach minimum accumulation levels between September and November mainly due to the low inflows and relatively high electricity demand during the summer. HE Pirot shows more fluctuating trend of its reservoir level because of lower accumulation over power output ratio. Drop that occurred from February to mid-March is due to low winter precipitations.

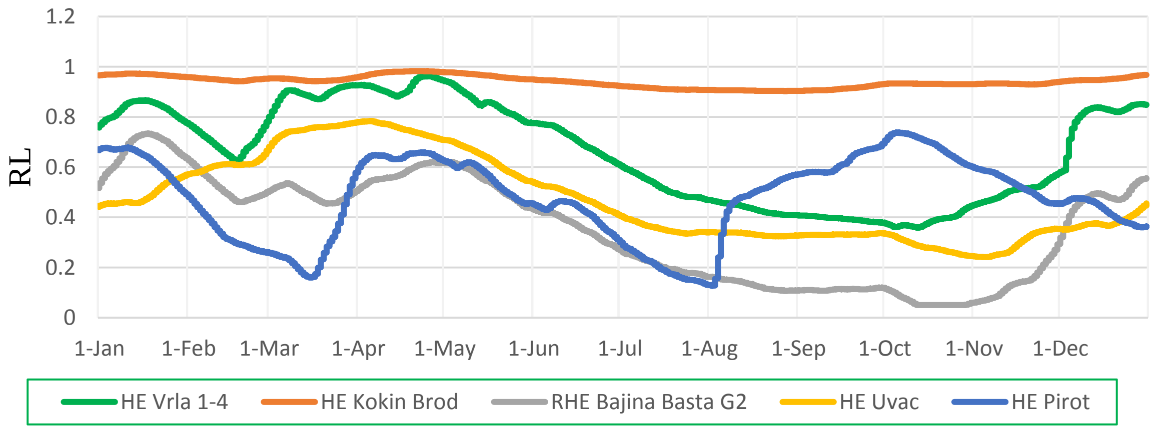

Figure 27 Hourly values of reservoir level for hydropower plants with large accumulation in Serbia

Reservoir level of hydropower plants with smaller accumulation capacity is illustrated in Figure 28, from where it can be seen how reservoir level of hydropower plants with smaller accumulation differ substantially from those with larger accumulation. Reason of high fluctuating trend lies in small size of the accumulation, so when the hydropower plant works at its nominal power it drains water from the storage within few hours or days. These types of hydropower plants are often used for meeting peeks in electricity demand.

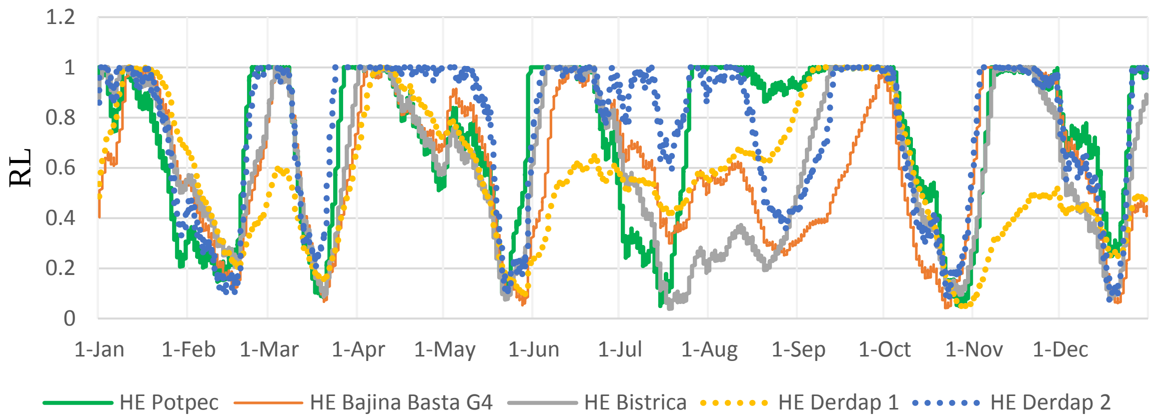

Figure 28 Hourly values of reservoir level for hydropower plants with small accumulation in Serbia

Scaled inflows have been calculated for accumulation hydropower plants according to equation (15) and they are divided by the type of inflows that is used for each hydropower plant. Hydropower plants with inflows that look like Figure 2, are presented in Figure 29. Scaled inflows are in direct correlation with river discharge rates. Because of that, higher values usually occur during spring and winter months, especially during December where their values are often higher than 1. The lowest values of scaled inflows usually occure from June to October, when river discharge rates are the lowest. Each hydropower plants has different value of scaled inflow because of different river hydrology.

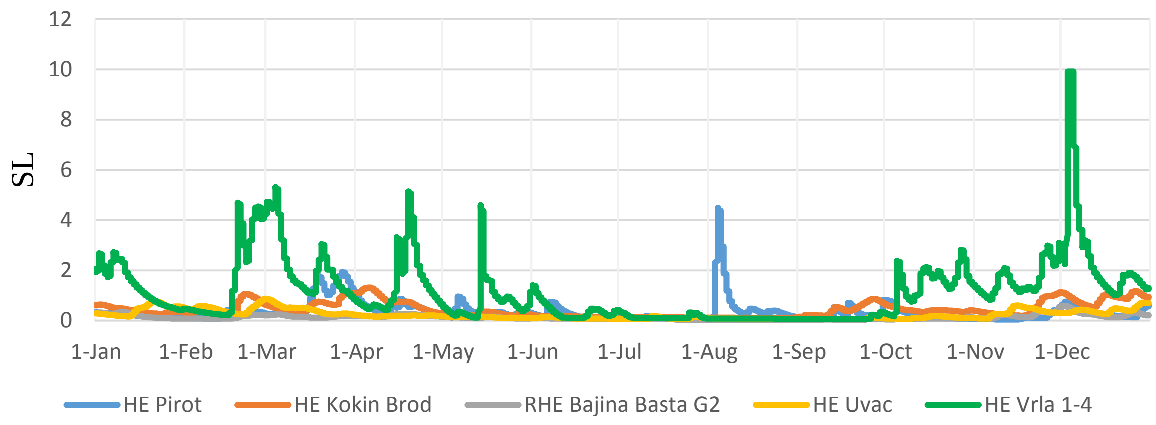

Figure 29 Hourly values of scaled inflows for hydropower plants in Serbia

Scaled inflows of hydropower plants that use modified distribution of inflows are illustrated in Figure 30. Scaled inflows are in direct correlation with river discharge rates. Because of that, higher values usually occure during the spring and winter months, especially during December where their values are often higher than 1. The lowest values of scaled inflows usually occure from June to October, when river discharge rates are the lowest. The drop that occurs in September is due to extremely low percitipation.

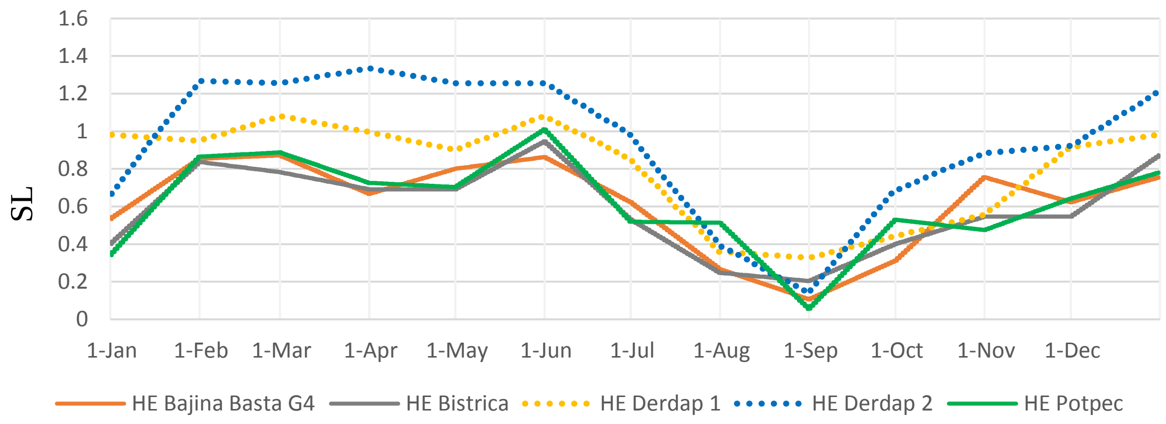

Figure 30 Hourly values of scaled inflows for hydropower plants in Serbia that uses modified hourly river flow distribution

4.6.2.4. Alternative scenarios

This section describes new production capacities installed in 2020 and 2030 according to cases A, B and C [60]. In addition to the list of power plants presented in Table 28. In Table

37 are new capacities of power plants in 2020 presented. They are added to the existing ones from 2010. New capacities in 2030 are presented in Table 38. Similar as before they are also added to the existing ones from the reference scenario. Case C has no new thermal power plants because it is high RES scenario. Instaled capacities of wind and solar power plants are increasing in future. All technology and cost related data for new power plants are determined according to some scientific publications and imported into model[25][24]. Thermal power plants are not planned to instal in future for all scenarios.

Table 37 New capacities of Serbia in 2020

	Case A and B	**case C**
	MW	**MW**
Hydropower plants	458	458
Thermal power plants	-	-
Solar power plants	10	255,35
Wind power plants	500	3267,5
Total	968	3.981

Table 38 New capacities of Serbia in 2030

	Case A and B	**case C**
	MW	**MW**
Hydropower plants	750	750
Thermal power plants	-	-
Solar power plants	200	3.267,5
Wind power plants	600	3.267,5
Total	1.550	7.285

Availability factor of hydropower plants in 2010 is applied to new hydropower plants in 2020 and 2030.

Availability factor for solar power plants is illustrated in Figure 31. Hourly values of power output for solar power plants are obtained from Renewables ninja and corrected using values of global irradiation from pvgis [29] [30]. Corected values of hourly power output for solar power plants are representing availability factor and are used in 2020 and 2030 in all three cases Electricity production of solar power plant is oscilating on daily basis because solar power plants are producing electricity only during the day. Highest electricity production is achived in spring because in that period there are lot of sunny days. Low production with high oscilations are in winter because days are cloudy with often precipitations.

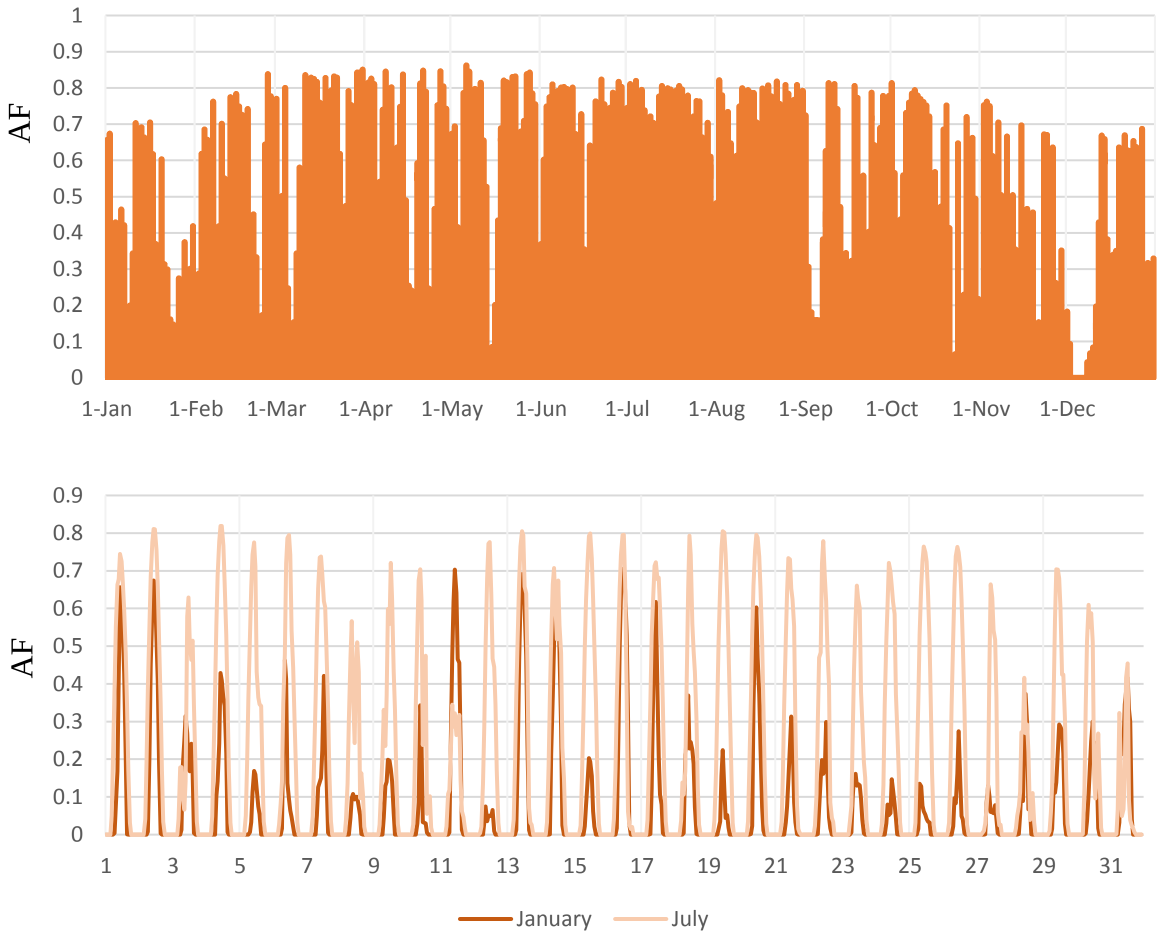

Figure 31 Hourly values of availability factor for solar power plants in Serbia

Availability factor for wind power plants can be seen in Figure 32. Hourly values of power output for wind power plants are obtained from Renewables ninja and they represent availability factor used in 2020 and 2030 for all three scenarios [29]. It is clear that from mid-May til September wind power plants operate at lower values due to lack of wind during summer. During the whole year there are oscilations in power production from wind turbine because of stohactic nature of wind.

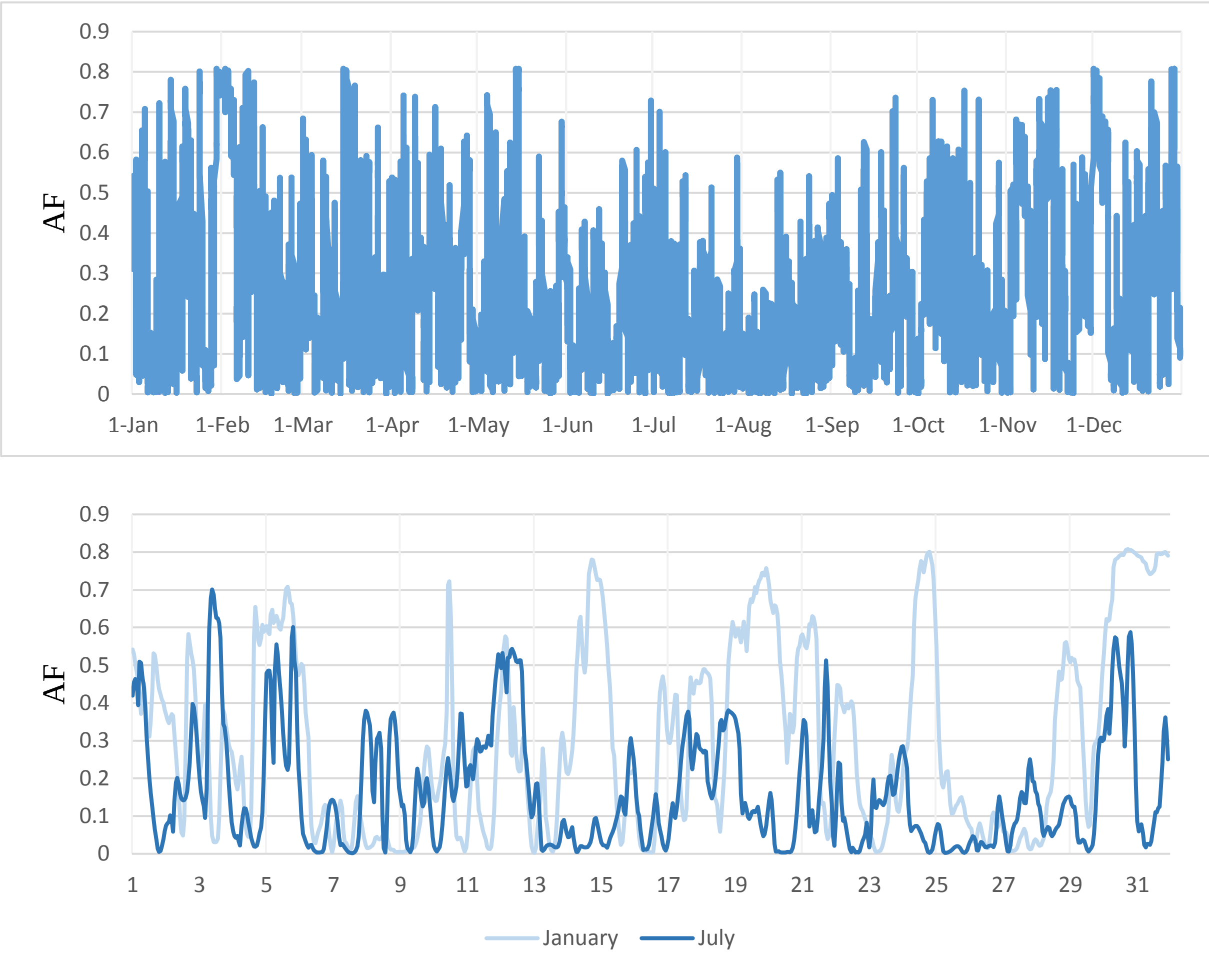

Figure 32 Hourly values of availability factor for wind power plants in Serbia

4.7. Kosovo

The capital citiy and at the same time the largest city of Kosovo is Pristina. According to national census population in 2011 is 1.734.000 [19]. Figure 33 shows transmission network of Kosovo as well as position of larger power plants and substations as they were in 2010. Relativly uniform electricity demand is established during the whole year. The 2010 was a year with high amount of percitipations which had great influence on electricity production from hydropower plants. Kosovo has several large substations located near cities of Prisitna, Peja and Perizaj. It can be seen that Kosovo has 400 kV transmission lines between Montenegro, Macedonia and Serbia. With Albania is connected through 220 kV transmission lines.

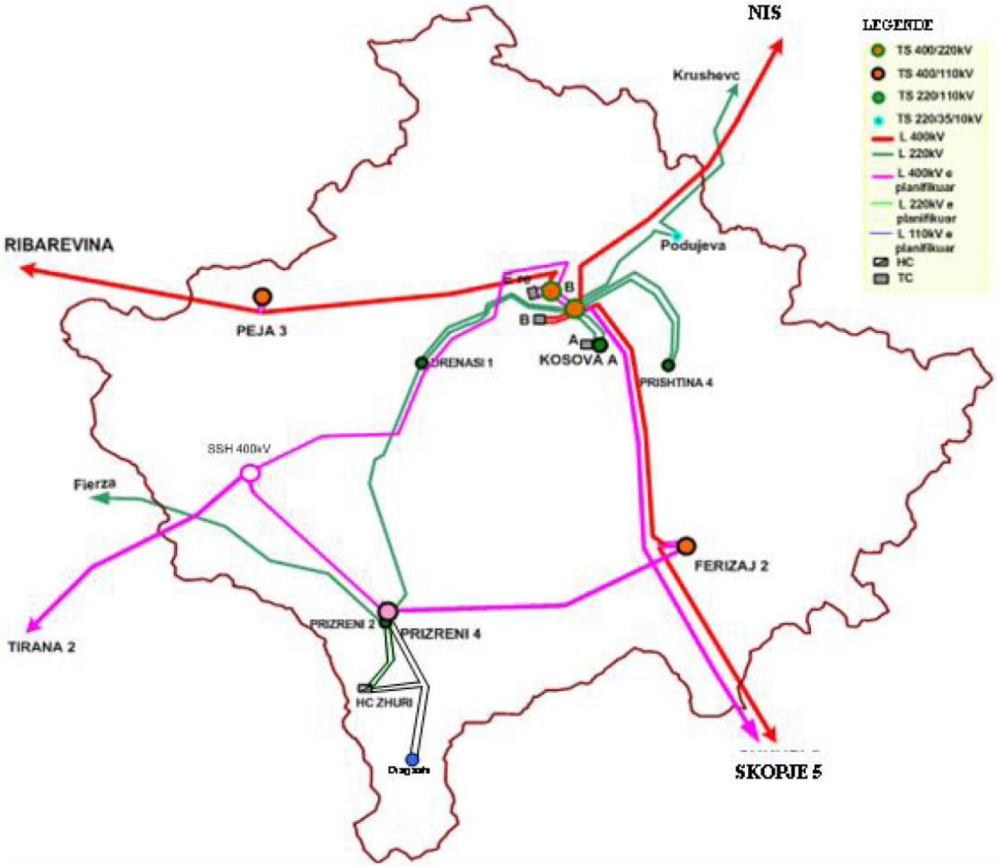

Figure 33 Transmission network of Kosovo with position of larger power plants and substations [13]

4.7.1. Electricity demand

4.7.1.1. Reference scenario

The electricity demand of Kosovo is presented in Figure 34. Overall annual electricity consumption of Kosovo in year 2010 amounted to 5.711,434 GWh [80]. During the winter months it is slightly higher than in summer due to the fact that almost 38% of population is using electricity for space heating [55]. Highest demand of 1155 MW has been recorded during January while the lowest is 185 MW and recorded in March. Electricity demand vary between 300 MW and 900 MW with average value of 652 MW.

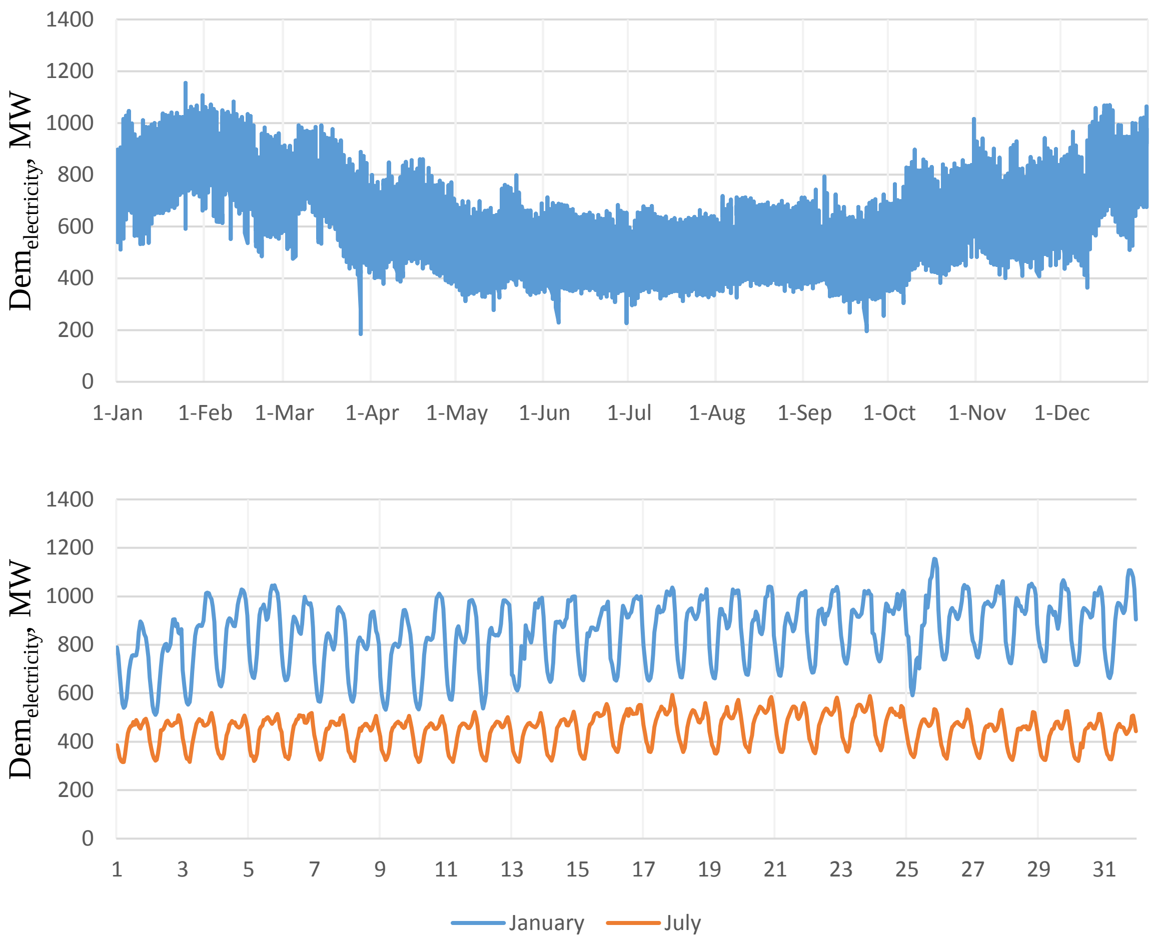

Figure 34 Hourly electricity demand of Kosovo

4.7.1.2. Alternative scenarios

According to demand forecasts for the year 2020 and 2030 electricity demand in Bosnia and Herzegovina should be 7.470 GWh and 7.180 GWh respectivley[20]. The hourly values of electricity demand presented in Figure 34 are scaled and used in all three scenarios whitihin a specific year. From there it is clear that demand in Kosovo is increasing from 2010 til 2020 and then fall from 2020 til 2030.

4.7.2. Electricity production

4.7.2.1. Reference scenario

The electricity production in Kosovo in 2010 consist of electricity produced by thermal power plants and hydropower plants. A list of electricity generating units can be seen in Table 39. Total installed capacity in 2010. was 960,9 MW of witch 915 MW are thermal power plans, 95 MW are accumulation hydropower plants, and 10,9 MW are small run-of-river hydropower plants. Installed capacities in 2010 are not sufficient to cover peak loads because highest electricity demand is 1.155 MW and total installed capacity is 960,9 MW which is lower than maximal demand by 194,1 MW. Diference between maximal demand and total installed capacities are imported from neighbouring countries. The highest share of installed capacities have thermal power plants and it amounts to 95,22%. Accumulation hydropower plants accounted for 3,64% of total installed capacities and run-of-river power plants have the smallest share of 1,13%. TE Kosovo B is largest power plant in Kosovo with installed power of 520 MW or 54,12% of total installed capacity.

Table 39 List of power plants in Kosovo

Unit	**Power Capacity**	**Technology**	**Fuel**	
	MW			
TE Kosovo A	395	STUR	LIG	[81]
TE Kosovo B	520	STUR	LIG	
HE Ujmani	35	HDAM	WAT	
HE Lumbardhi	8.8	HROR	WAT	
HE Dikance	1.34	HROR	WAT	
HE Radavac	0.28	HROR	WAT	
HE Burimi	0.48	HROR	WAT	

4.7.2.2. Thermal power plants

There are two thermal power plants in Kosovo. All of them are coal-fired. TE Kosovo A is the largest one with total installed capacity of 395 MW. Power plant flexibility data are calculated according to some scientific publications and are presented in Table 40. In addition to this, data related to the costs of running and operating units is also covered by the same publications[24][25]. Maximal efficiency for TE Kosovo A and B amounts to 34,15%, minimal efficiency is 29%, ramp up and ramp down rate amounts to 2,5% of nominal power per minute. Minimal partial load of TE Kosovo A amounts to 8,26% and for TE Kosovo B amounts to 11,87%.

Table 40 Technology related data for thermal power plants in Kosovo

Variable		Unit	
		TE Kosovo A	TE Kosovo B
Efficiency	**%**	34,15	34,15
Min Up Time	**h**	6	6
Min Down Time	**h**	1,5	1,5
Ramp Up Rate	**%/min**	0,025	0,025
Ramp Down Rate	**%/min**	0,025	0,025
Min Part Load	**%**	0,08258	0,118732
Min Efficiency	**%**	0,29	0,29
Start Up Time	**h**	6	6
CO2 Intensity	**kg/MW**	1.062	1.062

Table 41 shows cost related data for thermal power plants in Kosovo. From there it is clear that start up cost for TE Kosovo A is 48.000 EUR and for TE Kosovo B is 46.883 EUR.

Table 41 Cost related data of thermal power plants in Kosovo

Variable		Unit	
		TE Kosovo A	TE Kosovo B
Start Up Cost	**€**	48.000	46.883
No Load Cost	**€**	0	0
Ramping Cost	**€**	1,8	1,8

According to various of diferent sources planed outages due to maintenance were scheduled for TE Kosovo A and TE Kosovo B [82]. During this period TE Kosovo A and B was not able to produce electricity. The hourly values of outage factor for TE Kosovo A and B are determined according to (16) and graphical representation of outages are presented in Figure 35. Total annual electricity production of thermal power plants in 2010 was 4875,816 GWh or 96,8% of total electricity production. TE Kosovo A produced 1.682,358 GWh or 33,4% of total production and TE Kosovo B produced 3193,458 GWh or 63,4% of total electricity production [81]

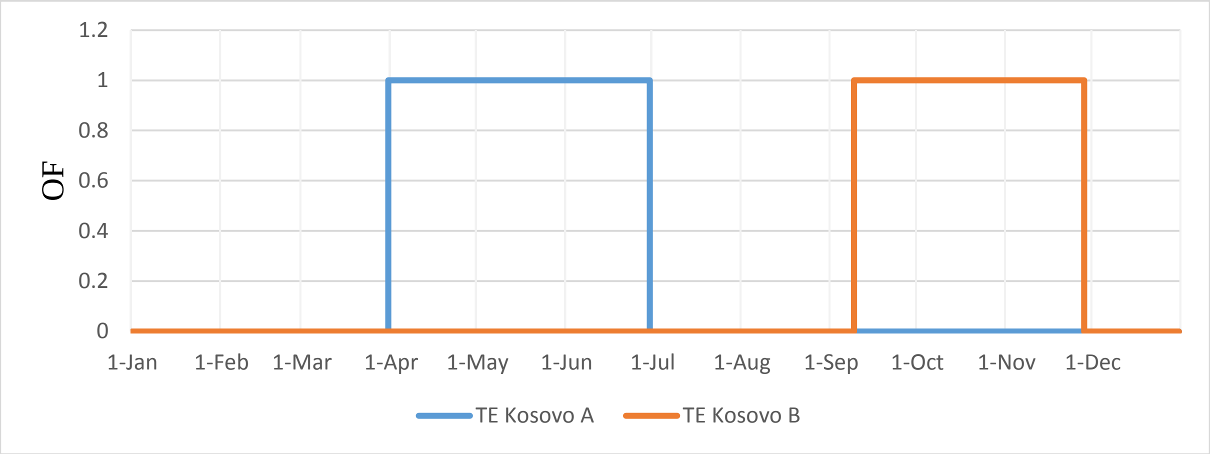

Figure 35 Hourly values of outage factor for thermal power plants in Kosovo

4.7.2.3. Hydropower plants

There is only one large accumulation hydropower plant in Kosovo. HE Ujmani located on the river Ibar with total installed capacity of 35 MW. Technology related data for hydropower plants are determined from various sources and calculated where not available. In Table 42 are presented technology related data for hydropower plants from where it is clear that maximal efficiency of HE Ujmani amounts to 81,24% and maximal efficiency of HE Lumbardhi amounts to 85%. Values from HE Lumbardhi are apllied to all run-of-river hydropower plansts in Kosovo. Total annual electricity production of hydropower plants in 2010 was 162 GWh or 3,22% of total electricity production.[81]

Table 42 Technology related data for hydropower plants in Kosovo

Variable		Unit	
		HE Ujmani	HE Lumbardhi
Efficiency	**%**	0,81242	0,85
Min Up Time	**h**	0	0
Min Down Time	**h**	0	0
Ramp Up Rate	**%/min**	1	1
Ramp Down Rate	**%/min**	1	1
Min Part Load	**%**	0	0
Min Efficiency	**%**	0,5	0,5
Start Up Time	**h**	1	1
CO2 Intensity	**kg/MW**	0	0

Technical data related to the power plants are presented in Table 43. From there it is clear that HE Ujmani has accumulation with volume of 350.000.000 m^3. Insled flow for run-of-river hydropower plants is calculated based on the they river flows obtained from hyperweb and the energy they produced in 2010 [83][81].

Table 43 Technical data of hydropower plants in Kosovo

Unit	Nominal power	Installed flow	Net head	Accumulation volume	Energy in accumulation	
	MW	m^3/s	m	m^3	MWh	
HE Ujmani	35	35,68	100	350.000.000	95.375	[81][84]
HE Lumbardhi	8,8	112				[81]
HE Dikance	1,34	41				
HE Radavac	0,28	215				
HE Burimi	0,48	41				

The availability factor for run-of-river hydropower plants has been calculated according to equation (1). The graphical presentation of AF's for HE Radavci and HE Burimi are illustrated in Figure 36. The AF (blue line) represents hourly values of all run-of-river hydropower plants, and availability factors for HE Radavci and HE Burimi are illustrated to show how production trend looks like for each unit. It is clear that from November til May run-of-river hydropower plants operate at higher capacity because of the high river discharge rates. From May til November there are some oscilations caused by low inflows due to low percitipations during summer.

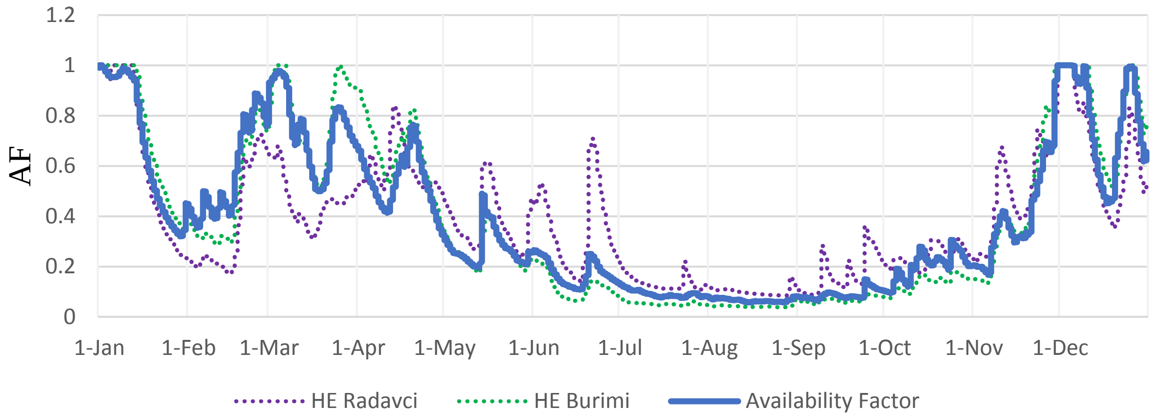

Figure 36 Hourly values of availability factor for run-of-river hydropower plants in Kosovo

Reservoir level of HE Ujmani is determined according to equation (6), and presented in Figure 37. From there it can be seen that HE Ujmani reach minimum accumulation levels between November and January mainly due to the low inflows and relatively high electricity demand due to planned outages in TE Kosovo A.

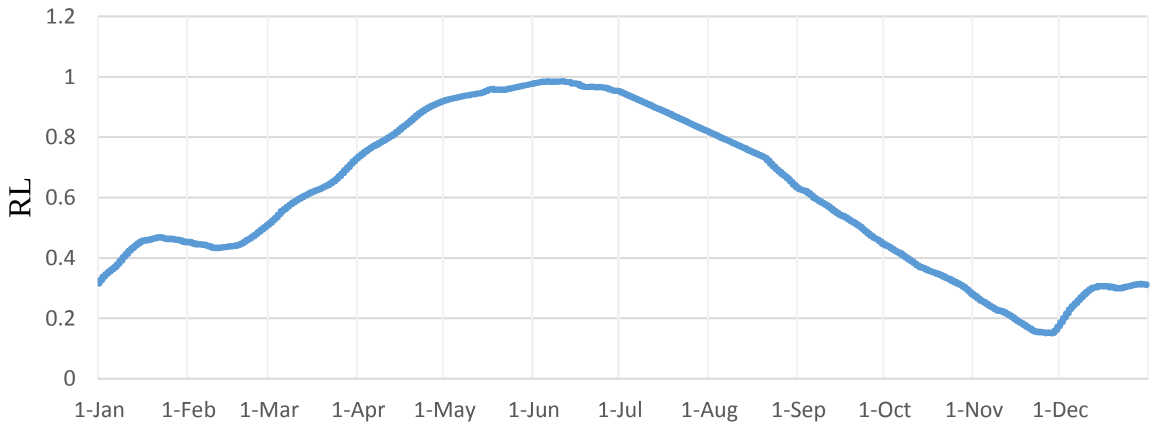

Figure 37 Hourly values of reservoir level for HE Ujmani

Scaled inflows that have been calculated according to equation (15), are presented in Figure 38. Scaled inflows are in direct correlation with river discharge rates. Because of that, higher values usually occure during the spring and winter months, especially during the December where their values are often higher than 1. The lowest values of scaled inflows usually occure from June to October, when river discharge rates are the lowest.

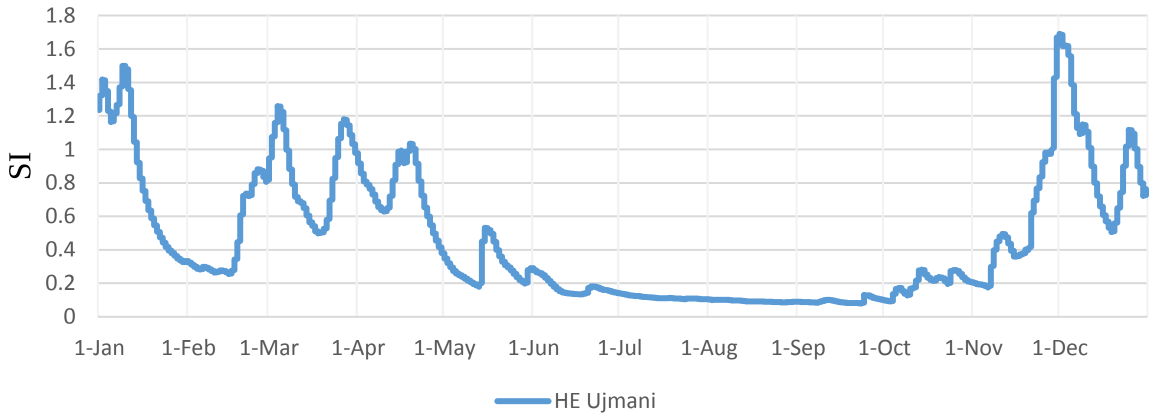

Figure 38 Hourly values of scaled inflows for HE Ujmani

4.7.2.4. Alternative scenarios

This section describes new production capacities installed in 2020 and 2030 according to the cases A, B and C [85]. In addition to the list of power plants presented in Table 39, in Table 44 are new capacities of power plants in 2020 presented. They are added to existing ones from the reference scenario. New capacities in 2030 are presented in Table 45. Similar as before they are also added to the existing ones from the reference scenario. Case C has no new thermal power plants because it is high RES scenario. Installed capacities of wind and solar power plants are increasing in future. All technology and cost related data for new power plants are determined according to some scientific publications and imported into model [25][24].

Table 44 New capacities of Kosovo in 2020

	Case A and B	case C
	MW	MW
Hydropower plants	16	16
Thermal power plants	600	0
Solar power plants	3	53,78
Wind power plants	140	812,04
Total	759	881,84

Table 45 New capacities of Kosovo in 2030

	Case A and B	case C
	MW	MW
Hydropower plants	20	20
Thermal power plants	1.800	0
Solar power plants	200	812,04
Wind power plants	200	812,04
Total	2.220	1.644,08

Availability factor for solar power plants is illustrated in Figure 39. Hourly values of power outputs for solar power plants are obtained from Renewables ninja and corrected using values of global irradiation from pvgis [29][30]. Corected values of hourly power output for solar power plants are representing availability factor and are used in 2020 and 2030 in all three cases. The electricity production of solar power plant is oscilating on daily basis because solar power plants are producing electricity only during day. The highest electricity production is achieved in spring because in that period there are lot of sunny days. Low production with high oscilations are in winter because days are cloudy with often precipitations.

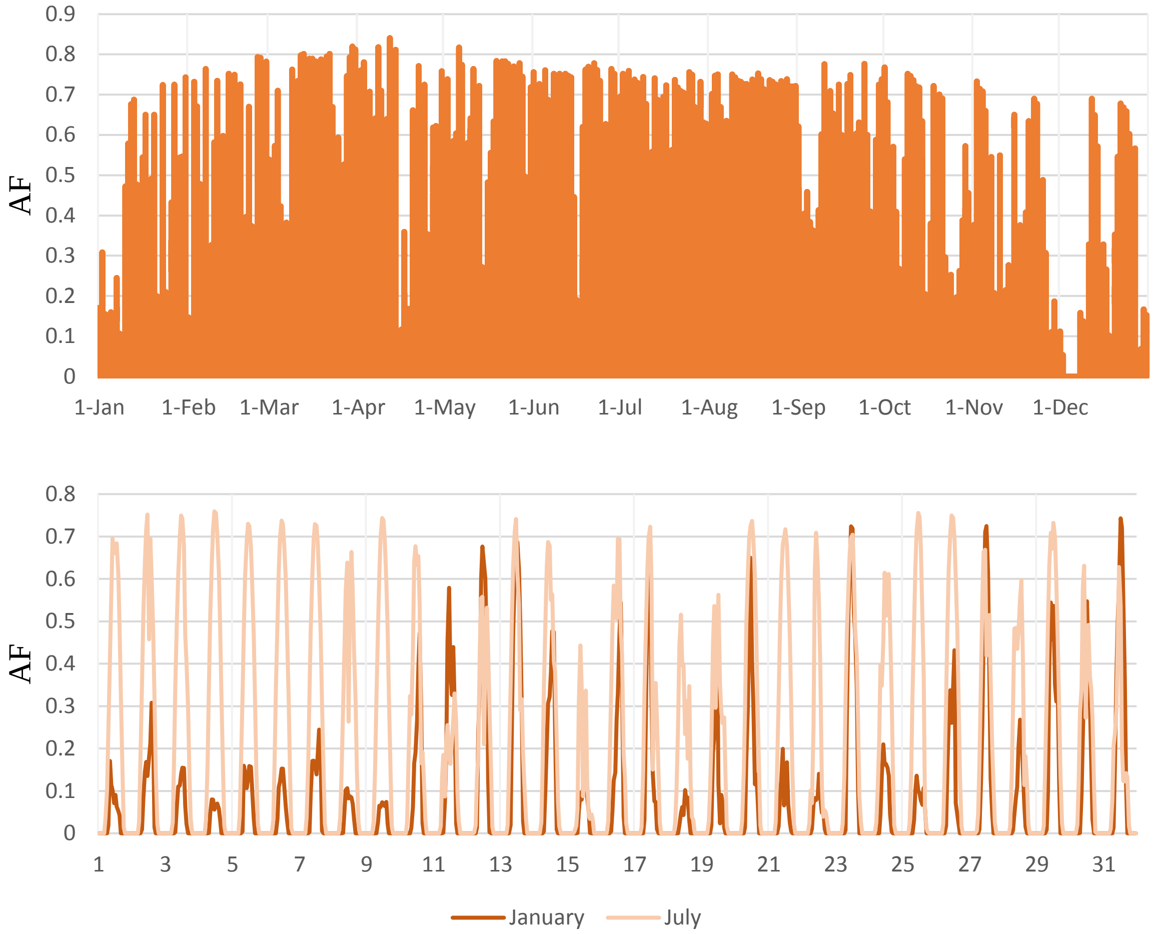

Figure 39 Hourly values of availability factor for solar power plants in Kosovo

Availability factor for wind power plants can be seen in Figure 40. Horly values of power output for wind power plants are obtained from Renewables ninja and they represent availability factor used in 2020 and 2030 for all three scenarios [29]. It is clear that from mid-May til September wind power plants operate at lower values due to lack of wind during summer. During the whole year there are oscilations in power production from wind turbine because of stohactic nature of wind.

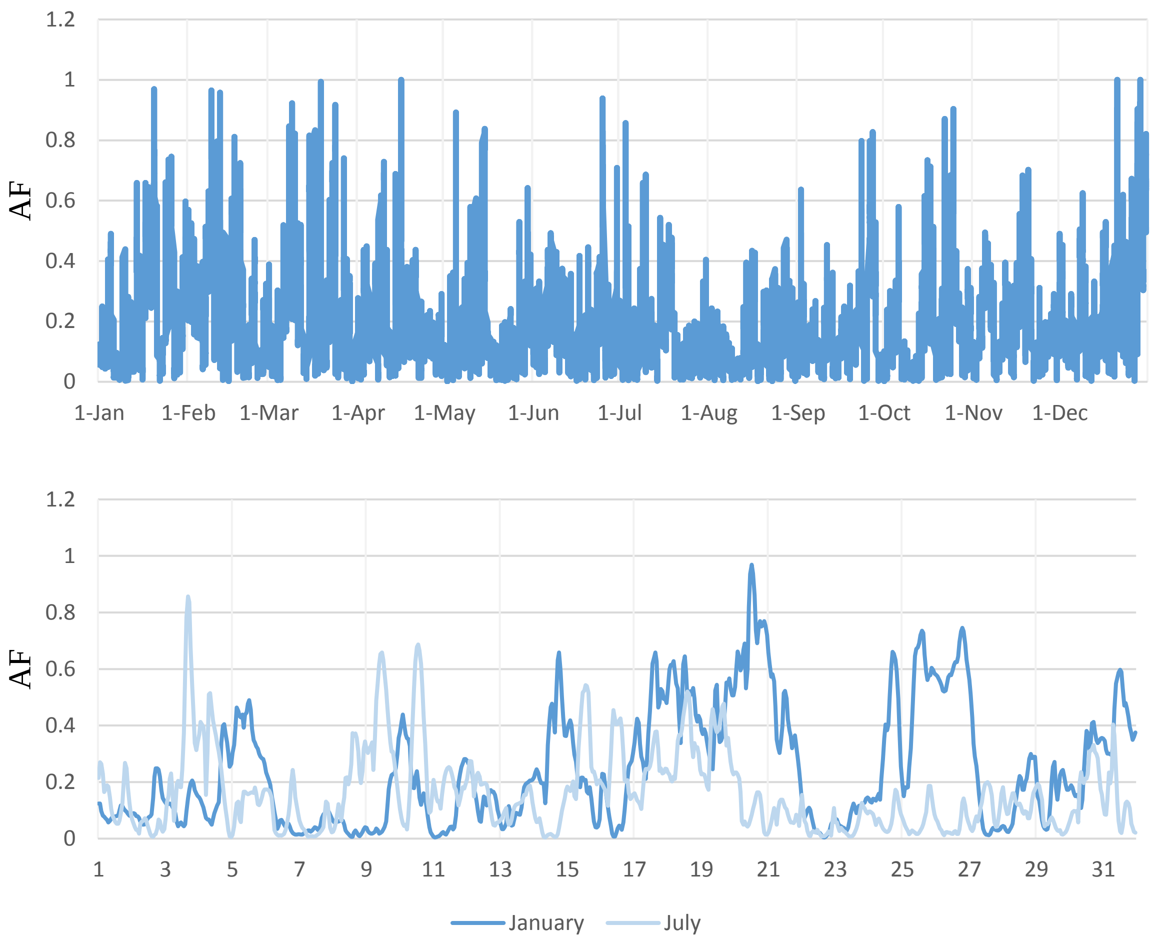

Figure 40 Hourly values of availability factor for wind power plants in Kosovo

5. RESULTS AND DISCUSION

5.1. Reference scenario

In the following section results from the Reference scenario are presented and described in more detail. They represent approximated symulations of power systems in four Western Balkan countries. The reference year chosen for this analysis is 2010. In order to validate accuracy of the model, simulated rezults have been compared to real world data, obtained from various sources such as national reports [27][34][63][81], EU Transparency platform [11] or other power sector related publications.

5.1.1. Common results

The common results are series of data that are equal for all countries. They are being used for comparison of reference year scenario and alternative future scenarios. Most significant results are average electricity price, cross border flows, peek loads, net import and fuel mix of electricity production.

Within common results, most important one is value of average price of electricity that is calculated by Dispa-SET. The average price of electricity in Reference scenario sums up to 24,731 €/MWh. The total electricity consumption of the whole simulated area is 56,155 TWh, with a peak load of 10.390 MW.

Table 46 presents values of cross border flows within each country in the Wester Balkans region and cross border flows with the rest of the world (RoW). RoW is a variable that represents all countries that are neighbouring the simulated zone. Serbia has the highest values of imports and exports between the countries from the RoW. This is mainly because Serbia is a country with higest number of neighbouring countries. Montenegro has lowest value of both exports and imports between countries from the ROW. Within analysed countries, maximal value of annual electricity exchange is recorded between Serbia and Bosnia and Herzegovina while the minimum value is recorded between Kosovo to Montenegro.

Table 46 Cross border flows within simulated region in 2010

TO \ FROM		BA	ME	RS	XK	RoW	Total Import
		GWh	GWh	GWh	GWh	GWh	GWh
BA	**GWh**	-	938	2.590	-	223	3.752
ME	**GWh**	1.496	-	1.443	672	129	3.741
RS	**GWh**	925	317	-	1.009	5.298	7.551
XK	**GWh**	-	2.029	1.354	-	608	3.992
RoW	**GWh**	4.042	532	2.906	2.146	-	9.627
Total export	**GWh**	6.464	3.816	8.295	3.828	6.260	-

Table 47 shows total electricity demand, peak load and net imports for each country. They describe key elements of each analysed power system. The negative value of net imports indicates that more power is exported than importet from other countries. It can be seen that Serbia has the highest electricity demand and peak load, which is expected due to the highest population and industrial production. The net balance of import and export shows that all countries export electricity except for Kosovo. The main reason why Kosovo imports electricity is because Kosovo's peek load is much higer then the total combined installed capacities of all power plants. Unlike Kosovo, Bosnia and Herzegovina has higest exportations mainly due to relatively large amount of hydropower plants. As said before, year 2010 is a year with high percitipations which have great influence on electricity production from those hydropower plants. Sum of total net imports is -3,3676 TWh which represents amount of electricity that is exported from simulated zone into the RoW.

Table 47 Country specific data related to electricity demand, peak load and net imports

	Electricity Demand	Peak Load	Net Imports
	TWh	MW	TWh
BA	12,0745	2173	-2,7118
ME	3,9258	813	-0,0756
RS	34,4433	6601	-0,7444
XK	5,7113	1155	0,1642

DispaSET is a neat tool that, beside numerical optimization module, also has the ability for visual representation of rezults and one of them is fuel mix in electricity production for each country illustrated in Figure 41 . On the legend, located on the right side of the diagram, is a colour scheme representing various types of energy sources. For example water is marked with blue colour, Lignite with dark red, Gas with pink and imported electricity with green colour. In the Reference scenario the power sector of the Western Balkans region contains only hydropower plants and coal fired thermal power plants, but also a small amount of gas fired kombi power plants. The gas fired thermal power plants are installed only in Serbia, but because of relatively small annual production they are hard to see on the diagram.. The year 2010 was one of the rainiest years in the last decade and that is the reason why the share of hydro power was so high in comparison to some earlier years. This wasn't the case in Kosovo, where almost all electricity production depends on lignite thermal power plants.

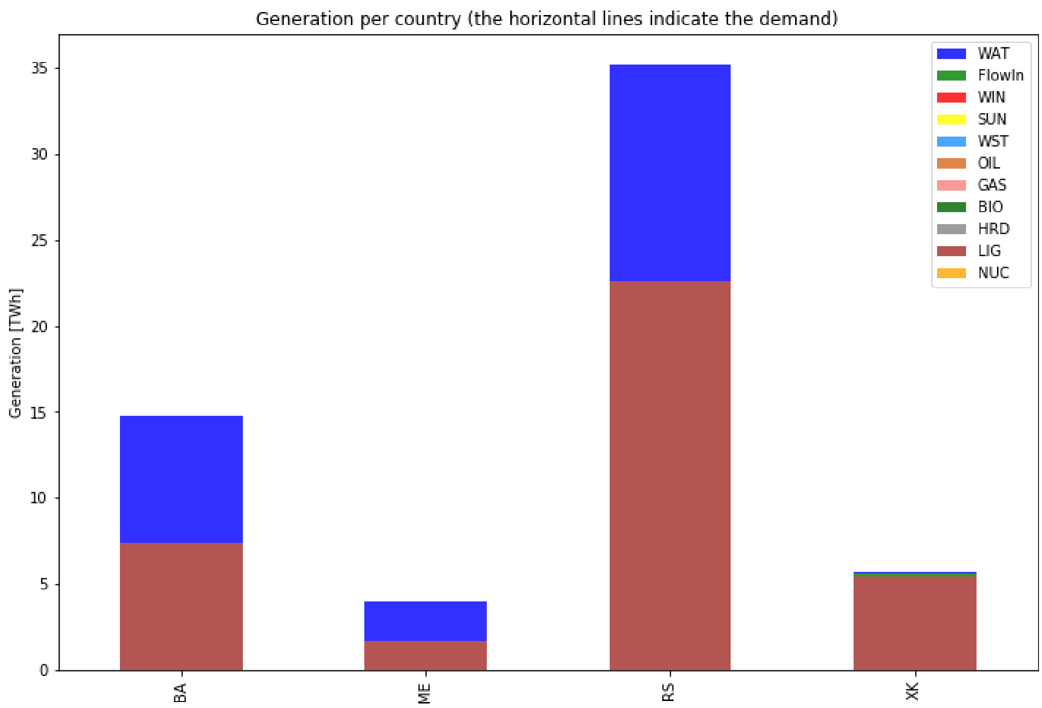

Figure 41 Fuel mix in electricity production for reference year

5.1.2. Montenegro

The power dispatch curve of Montenegro is shown in Figure 42. It represents a way of how electricity demand is being met using various generating units. In power dispach curve import, export and storage level of accumulation hydropower plants are also included. In order to better represent the seasonal differences in production, power dispatch curve is shown for January and June. On the right side of the diagram, is a colour scheme representing which colour and pattern represents certain fuel type. Electricity demand is marked with black colour, blue colour is electricity produced by hydropower plants, light red is electricity produced by coal thermal power plants, negative values of green colour is export while positive values of same colour is import. Values on the right axis are related to hourly values of energy stored in hydropower plant accumulations, which are marked with dotted line. In the same figure below power dispatch curve is the commitment status of all generating units within country for every hour. Black colour stands for electricity production of unit with nominal power output. Grey colour stands for reduced power production and white colour is when unit doesnt produce electricity. Thermal power plant TE Pljevlja is producing electricity at nominal power during all year except for period of planned outages scheduled in May. During the outages in TE Pljevlja electricity is reimbursed with increased hydropower production and importations. All accumulation hydropower plants are clustered and calculated as one unit, and same is applied to run of river hydropower plants. Regarding the river hydrology, run of river hydropower plants worked at nominal power in periods during winter and spring when there are lot of rainfalls.

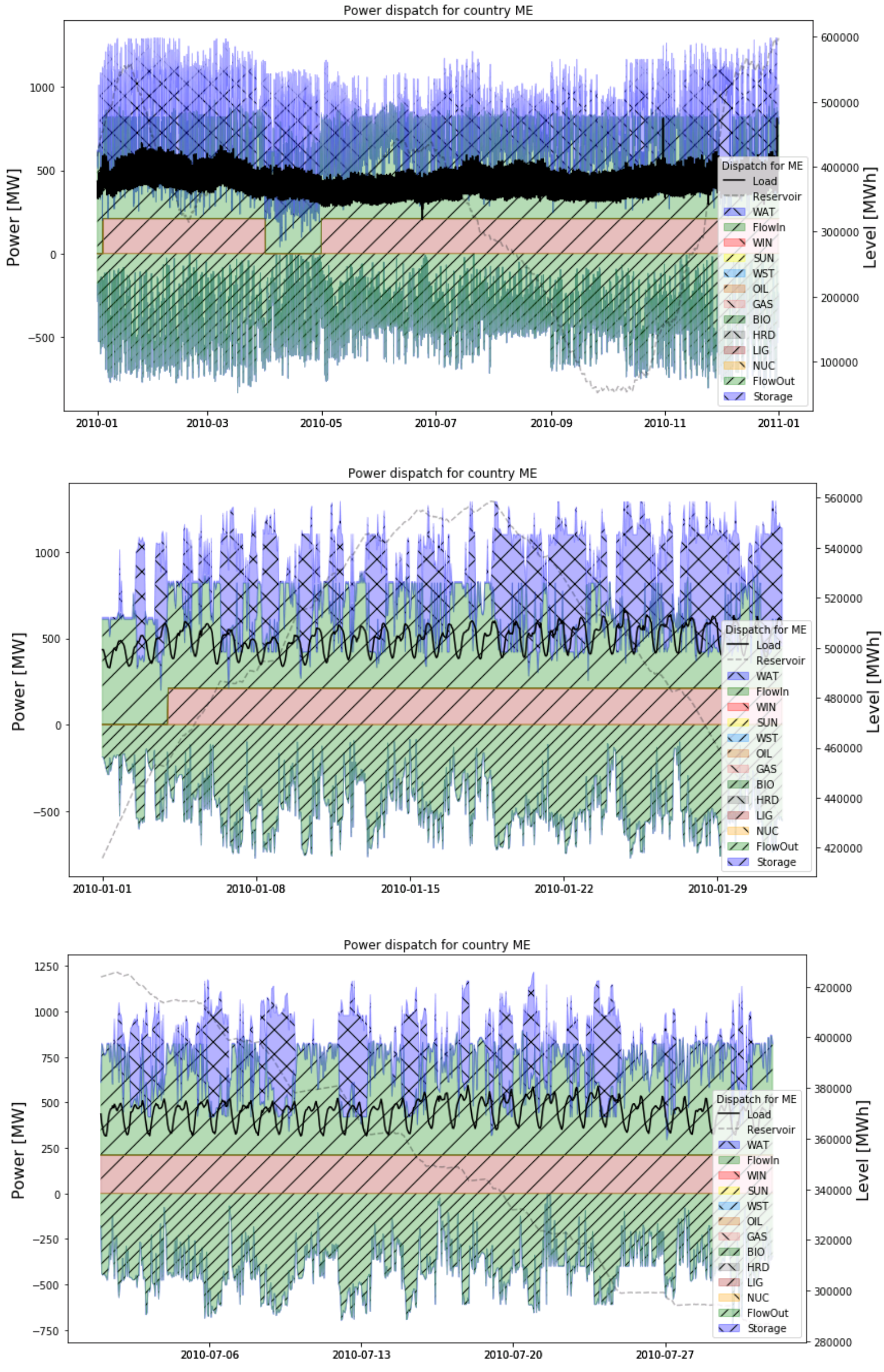

Figure 42 Power dispatch curve of Montenegro for whole year (top), January (middle) and July (bottom)

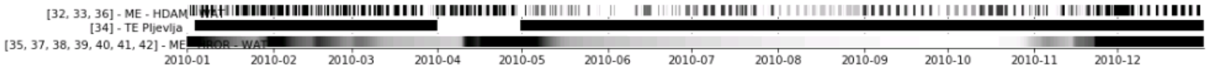

Figure 43 Unit cycling of power plants in Montenegro

The comparison of electricity production between the national reports and the calculated values from Dispa-SET, is presented in Table 48. The deviation between electricity production from national reports and calculated values using Dispa-SET exists mainly because of accuracy of input data and lack of technology data for all power plants. There isn't much deviation between these two values and the goal is that they are below 10 % in all countries in order to validate simulation model of electricity production.

Table 48 Electricity production of Montenegro in reference year

Unit	Estimated values from national reports [27]	Calculated values using Dispa-SET	Difference
	GWh	GWh	%
Thermal power plants	1.271,7	1.673,5	-10,2
Hydropower plants	2.749,6	2.327,9	10,2
Total production	4.021,3	4.001,4	-0,5

Since there are only three accumulation hydropower plants in Montenegro, DispaSET clusteres them into one single unit. The accumulation level of clustered units is shown in Figure 44. Results are valid because reservoir level line follows reservoir levels of accumulation hydropower plants that are given as input data into the model.

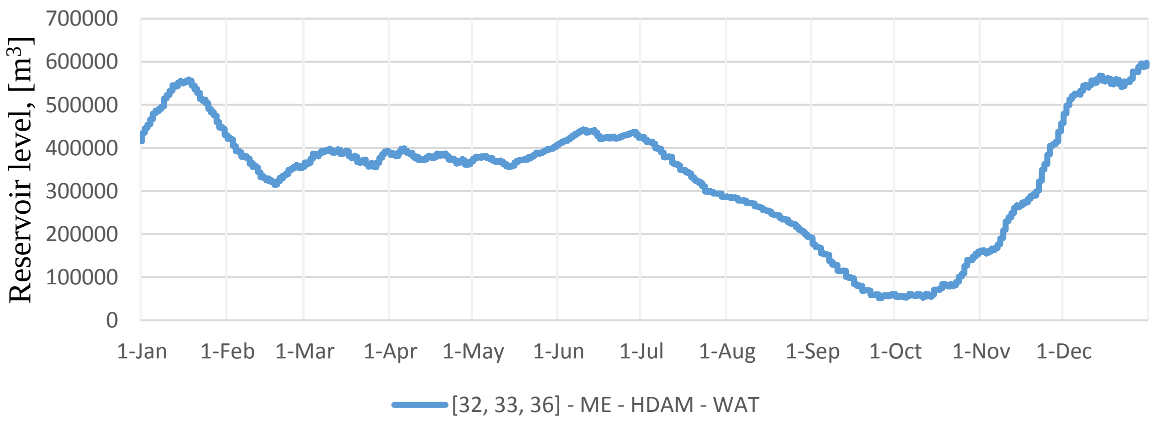

Figure 44 Reservoir level for clustered accumulation hydropower plants in Montenegro

5.1.3. Bosnia and Herzegovina

The power dispatch curve of Bosnia and Herzegovina is shown in Figure 45. It represents how electricity demand is met by using various power generation units. In power dispach curve import, export and storage levels of accumulation hydropower plants are also included. In order to to better represent the differences between different seasons power dispatch curve is shown again for the same months as for Montenegro. The same colour scheme describing certain fuel types is applied. Values on the right axis are related to hourly values of energy stored in accumulation hydropower plants, which are again marked with dotted lines. It is clear that thermal power plants have higher share in total electricity production in July than in January due to lower production capacity of hydropower plants during the summer. Figure 46 shows commitment status of all generating units within country in every hour of the year. As mentioned earlier some accumulation hydropower plants are clustered into one single unit. The same principle is applied to run of river hydropower plants. As an example "[10,12]-BA-HDAM-WAT" is a cluster of two accumulation power plant units, HE Rama and HE Dubrovnik. During the overhauls in the thermal power plants, electricity is reimbursed with increased hydropower production and import. Regarding to the river hydrology, run of river hydropower plants were in operation at nominal power capacity in winter and spring when there is usualy a lot of perticipitation.

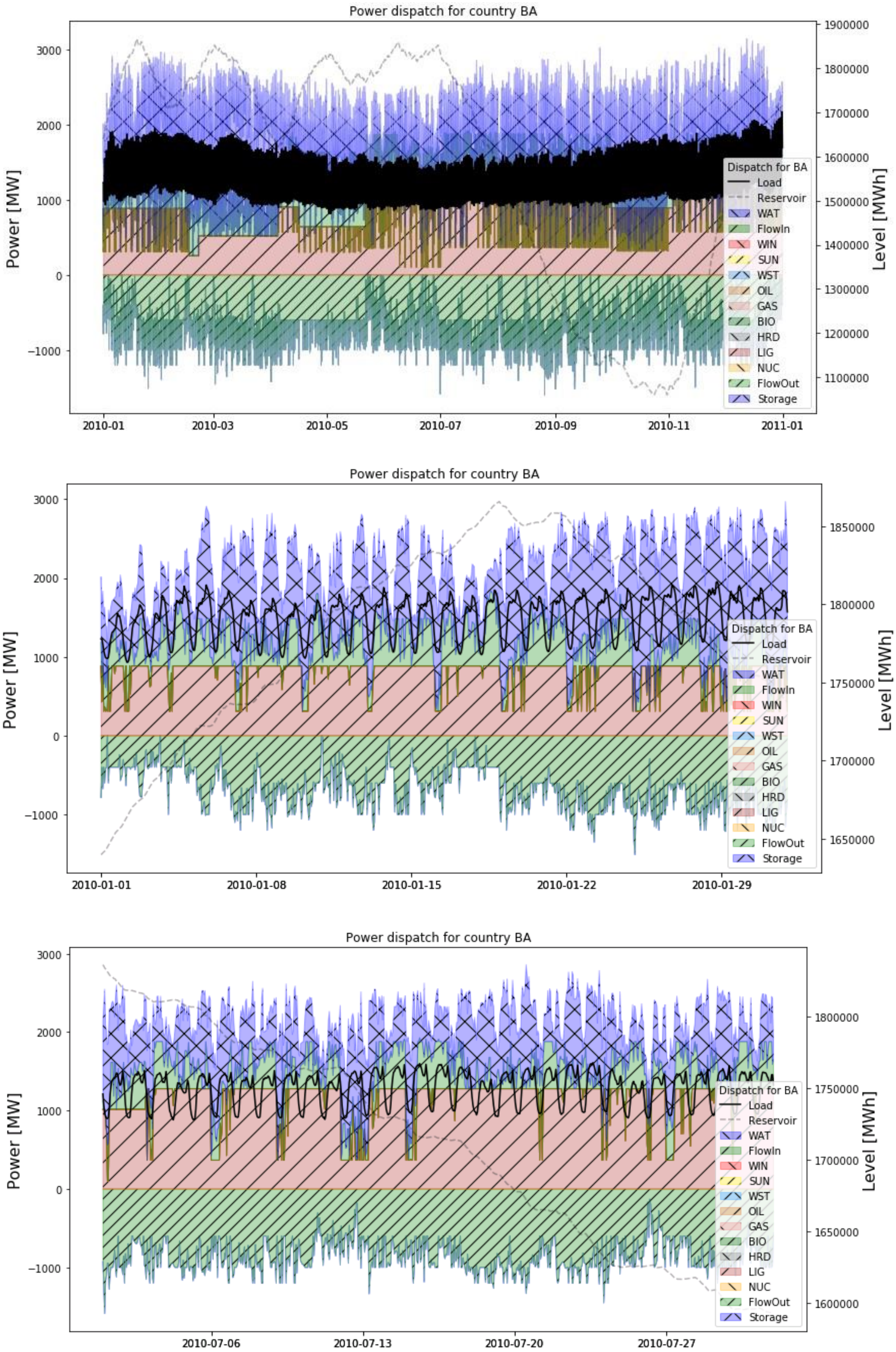

Figure 45 Power dispatch curve of Bosnia and Herzegovina for whole year (top), January (middle) and July (bottom)

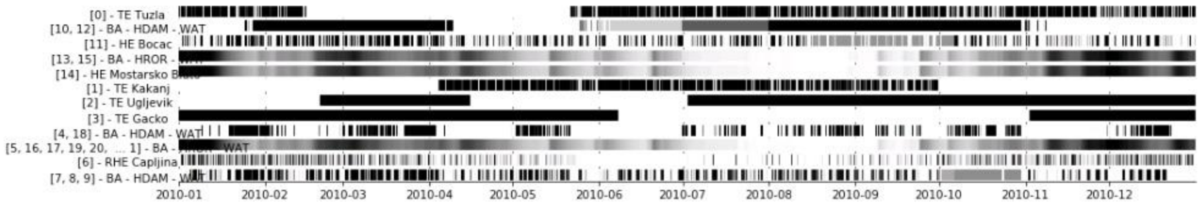

Figure 46 Unit cycling of power plants in Bosnia and Herzegovina

The comparison of electricity production between the national reports and the calculated values from Dispa-SET, are shown in Table 49. The deviation between electricity production from national reports and calculated values using Dispa-SET exists mainly because of accuracy of input data and lack of technology data for all power plants.. The difference in production is higher for hydropower plants than for thermal power plants. The calculated value of total electricity production does not deviate as much from estimated values from national report.

Table 49 Electricity production of Bosnia and Herzegovina in reference year

Unit	Estimated values from nation report [34]	Calculated values using Dispa-SET	Difference
	GWh	GWh	%
Thermal power plants	7.683	7.413	-0,74
Hydropower plants	7.870	7.373	0,74
Total production	15.553	14.786	-4,93

The accumulation hydropower plants are clustered into four units. The reservoir levels of each clustered unit is shown in Figure 47. Reservoir level of RHE Capljina appears as flat line because of its small accumulation in relation to other units as well as relatively small amount of accumulation usage. Results are valid because reservoir level lines follow actual reservoir levels of accumulation hydropower plants that are given as input data in to the model.

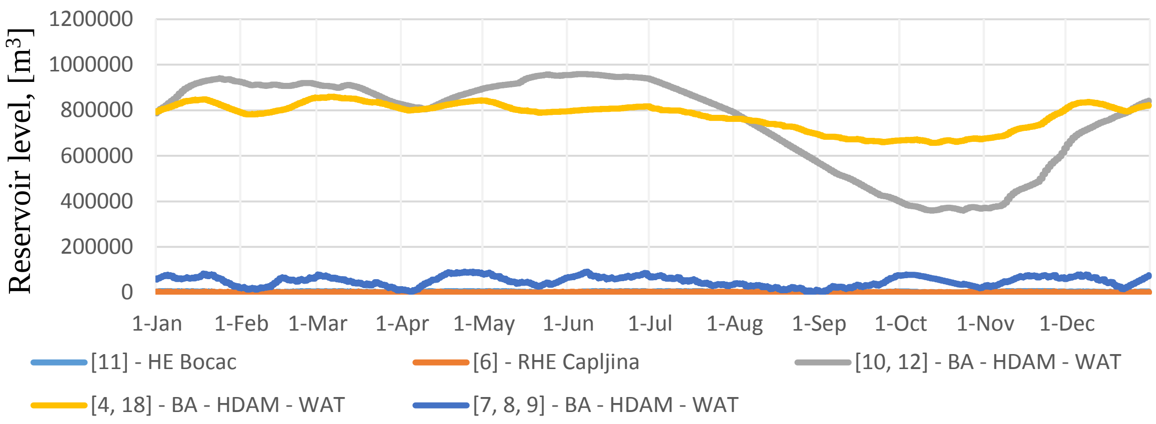

Figure 47 Reservoir level for clustered accumulation hydropower plants in Bosnia and Herzegovina

5.1.4. Serbia

The power dispatch curve of Serbia is shown in Figure 48. It represents how electricity demand, is met using various generating units. In power dispatch curve is also included import, export and storage level of accumulation hydropower plants. In order to have better representation of the differences between months, power dispatch curve is shown for January and June. On the legend, located on the right side of the diagram, is a colour scheme representing which colour and pattern represents certain fuel type. Values on the right axis are related to hourly values of energy in accumulation of hydropower plants, which is marked with dotted line. Electricity production of thermal power plants is higher in Janu Figure 49 shows commitment status of all generating units within country at every hour. Some of accumulation hydropower plants are clustered into one big unit, and same is applied to run of river hydropower plants. For example "[52, 53, 54]-RS-HROR-WAT" is cluster unit of three run-of-river power plants. During the overhauls in thermal power plants, electricity is reimbursed with increased hydropower production and import. Regarding to river hydrology, run of river hydropower plants worked at nominal power in periods during winter and spring when there is lot of rainfalls. It can be seen that unit TE Kolubara wasn't operating. Regarding to our input data and system configuration, unit commitment optimisation remove TE Kolubara from electricity production.

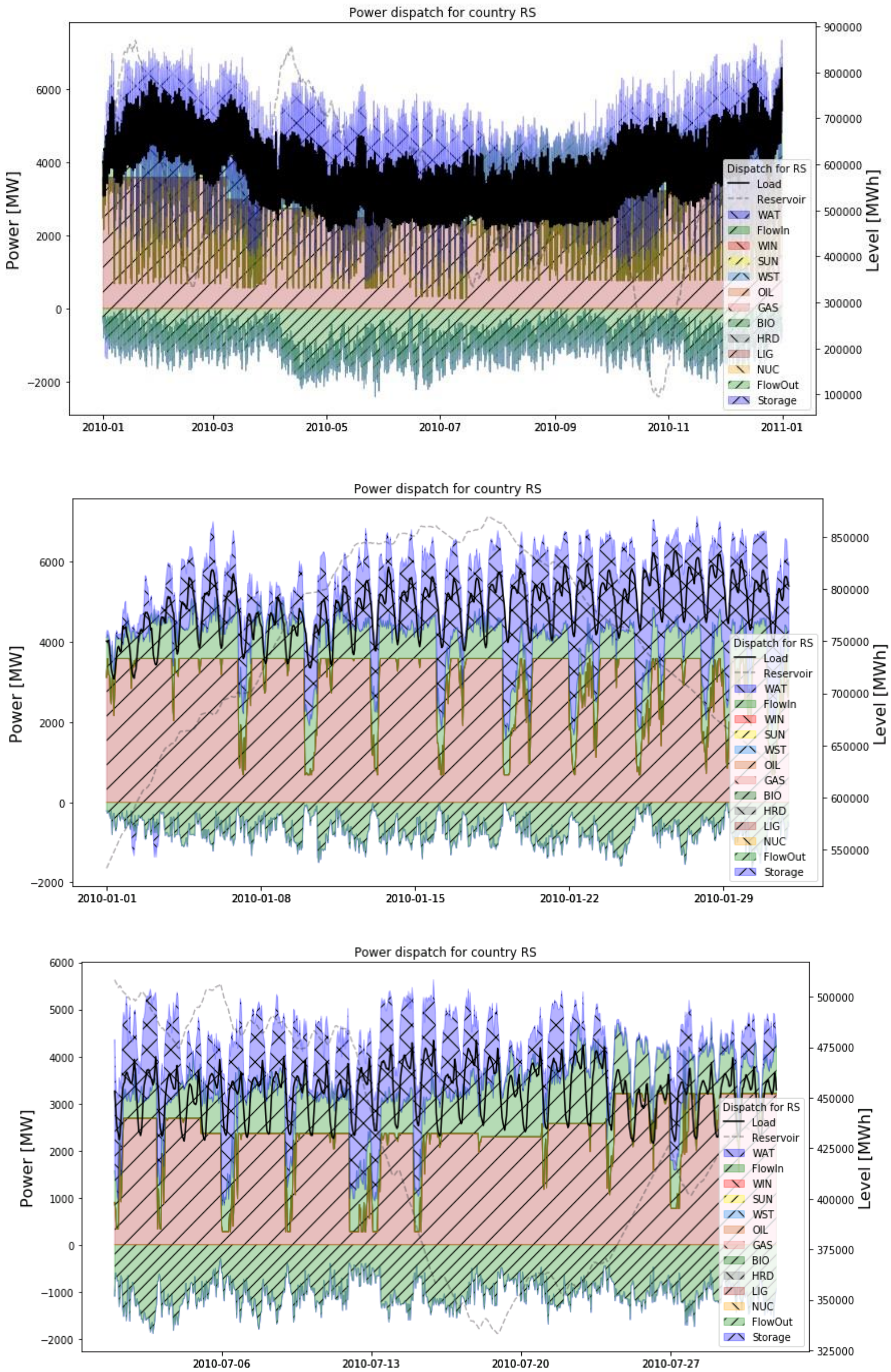

Figure 48 Power dispatch curve of Serbia for whole year (top), January (middle) and July (bottom)

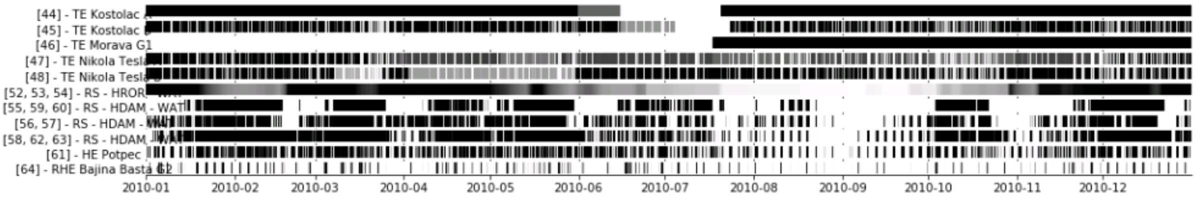

Figure 49 Unit cycling of power plants in Serbia

The comparison of electricity production between the national reports and the calculated values from Dispa-SET, are presented in Table 50. Deviation in electricity production of estimated values from national reports and calculated values using Dispa-SET occurs because of different optimisation variables in unit dispatch, accuracy of input data and unavailability of technology data for all power plants. Difference in production is higher for Thermal power plants than for hydropower plants. Calculated value of total electricity production does not deviate much from estimated value and it is important that this value is under 10 % in order to validate simulation model of electricity production in Serbia.

Table 50 Electricity production of Serbia in reference year

Unit	**Estimated values from nation report** [63]	**Calculated values using Dispa-SET**	**Difference**
	GWh	**GWh**	**%**
Thermal power plants	23.162	22.577	0,85
Hydropower plants	12.471	12.617	-0,85
Total production	35.633	35.194	-1,23

Accumulation hydropower plants are clustered, and reservoir level of clustered hydropower plants are shown in Figure 50. Reservoir level of HE Potpec appears as flat line because it has small accumulation in relation to other units. Results are valid because reservoir level line follows reservoir levels of accumulation hydropower plants that are given as input data to model.

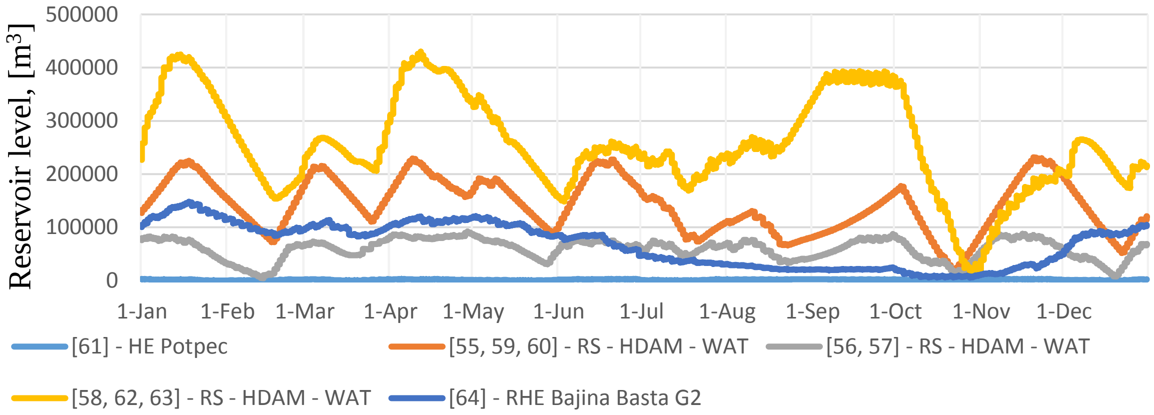

Figure 50 Reservoir level for clustered accumulation hydropower plants in Serbia

5.1.5. Kosovo

The power dispatch curve of Kosovo is illustrated in Figure 51. It represents how electricity demand, is met using various generating units. In power dispach curve is also included import, export and storage level of accumulation hydropower plants. In order to have better representation of the differences between months, power dispatch curve is shown for January and June. On the legend, located on the right side of the diagram, is a colour scheme representing which colour and pattern represents certain fuel type. Values on the right axis are related to hourly values of energy in accumulation of hydropower plants, which is marked with dotted line. It is clear that thermal power plants have higher share in total electricity production in July than in January due to lower production of hydropower plants during summer. Figure 52 show commitment status of all generating units within country at every hour. Black colour means that unit is producing electricity with nominal power output. Grey colour stands for reduced power production and white colour is when unit don't produce electricity. All run-od-river hydropower plants are clustered in one big unit. During the overhauls in thermal power plants, electricity is reimbursed with increased hydropower production and import. Regarding to river hydrology, run of river hydropower plants worked at nominal power in periods during winter and spring when there is lot of rainfalls. Electricity demand is mostly met by thermal power plants.

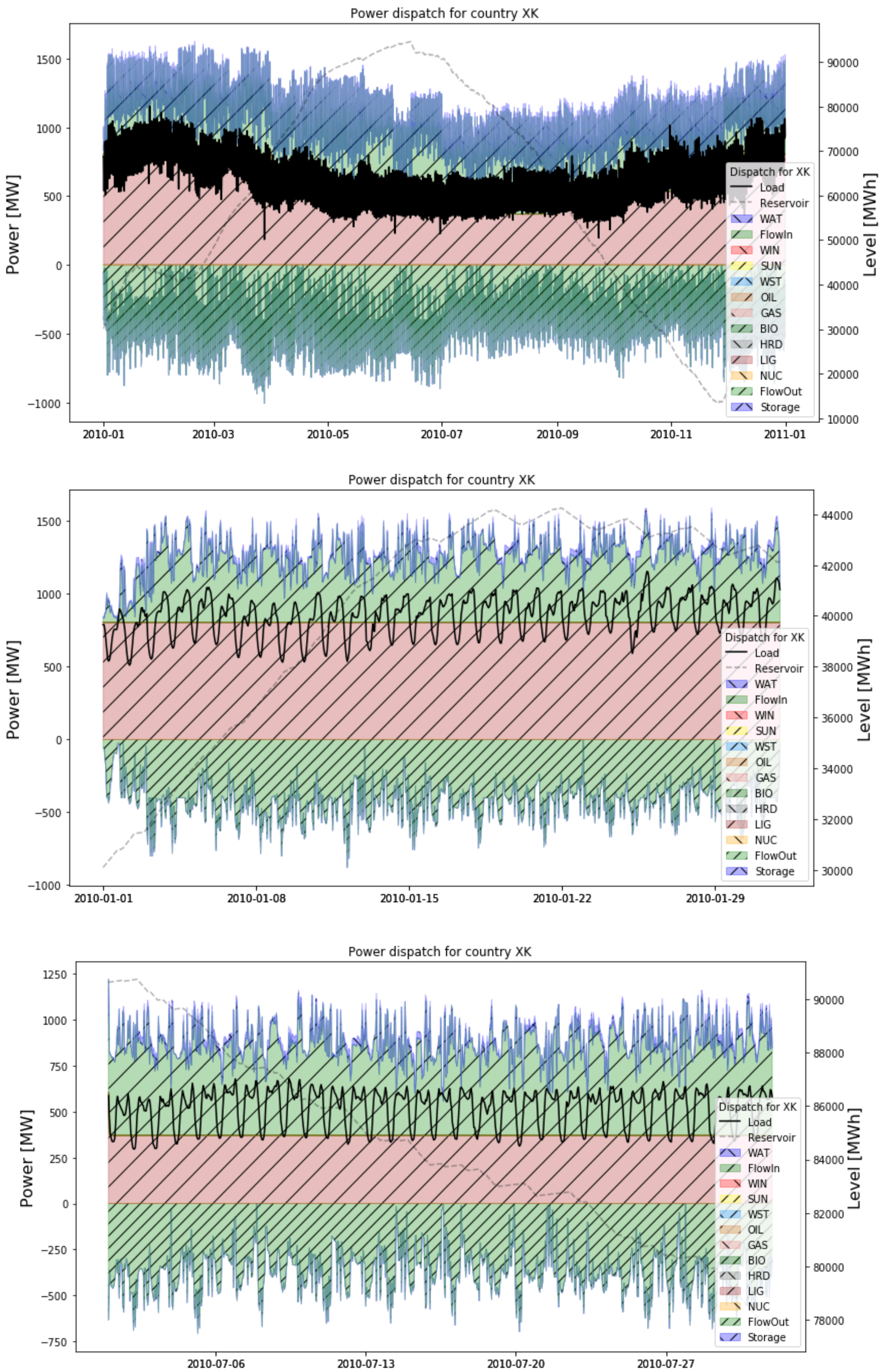

Figure 51 Power dispatch curve of Kosovo for whole year (top), January (middle) and July (bottom)

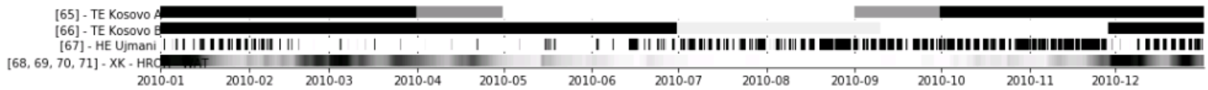

Figure 52 Unit cycling of power plants in Kosovo

The comparison of electricity production between the national reports and the calculated values from Dispa-SET, are presented in Table 51. Deviation in electricity production of estimated values from national reports and calculated values using Dispa-SET occurs because of different optimisation variables in unit dispatch, accuracy of input data and unavailability of technology data for all power plants. Calculated value of total electricity production does not deviate much from estimated value and it is important that this value is under 10% in order to validate simulation model of electricity production in Kosovo.

Table 51 Electricity production of Kosovo in reference year

Unit	**Estimated values from national report** [81]	**Calculated values using Dispa-SET**	**Difference**
	GWh	**GWh**	**%**
Thermal power plants	4.875	5.396	-0,5
Accumulation hydropower plants	162	151	0,5
Total production	5.037	5.547	10,1

Since there is only one accumulation hydropower plant in Kosovo, there is no clustering. The accumulation level of HE Ujmani is illustrated in Figure 53. Results are valid because reservoir level line follows reservoir levels of accumulation hydropower plants that are given as input data to model.

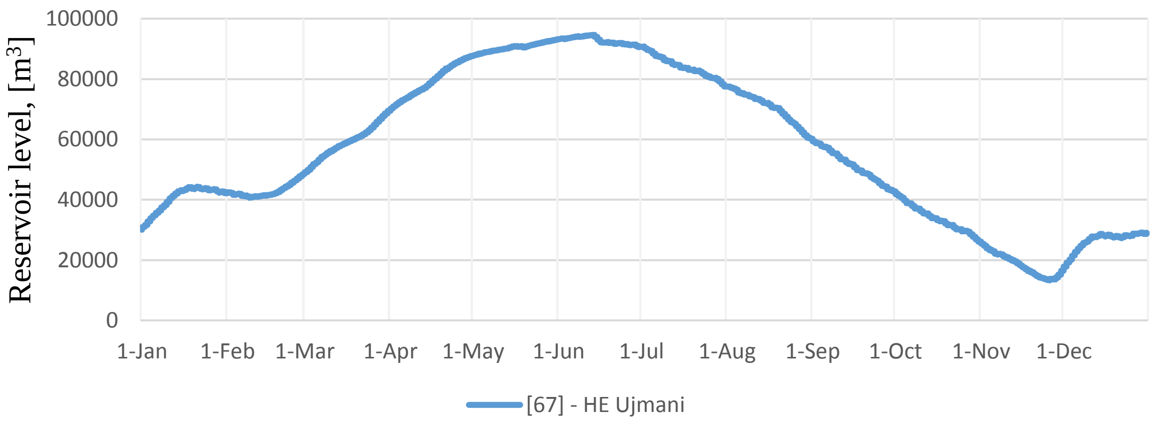

Figure 53 Reservoir level for clustered accumulation hydropower plants in Kosovo

5.2. Alternative Scenarios

In the following section results from alternative scenarios are presented and described in more detail. They represent approximated symulations of power systems in the four Western Balkan countries. The alternative scenarios are made for the years 2020 and 2030. As said before, each of alternative scenarios has three cases. The simulated results of all three analysed scenarios have been compared in order to validate each future strategy, and to check the behaviour of these power systems when high penetration of RES is proposed.

5.2.1. Common results

The aggregated statistical data of the whole region and for all thre analysed scenariosis presented in Table 52. Clearly the most important value is the average price of electricity. For both years, the highest average price of electricity is, as expected, obtained from reference scenario, where it ammounts to total of 21,565 EUR/MWh in the year 2020 and 18,749 EUR/MWh in the year 2030. The lowest average price of electricity has been calculated in the scenario C where it sums to total of 14,479 EUR/MWh in the year 2020 and 13,126 EUR/MWh in the year 2030. The main reason for such a decrease is the amount of cheap energy from renewable energy sources, mainly due to the low fuel costs. Average price of electricity is generaly higher in the year 2030 than in the year 2020 because of higher share of RES in total installed capacities. In all three cases (Case A, Case B and Case C) the total electricity consumption and the peak load are constant and higher in the year 2030. This is due to the fact that these values are external projectios of future trends as mentioned earlier. The total net imports in the whole region vary between -3,368 TWh, in Case A, and 0 TWh in Case B and Case C. When the total net imports sum up to 0 this either means that the four power sectors from the whole region are in an equilibrium, or that there is no exchange with the rest of the world.

Table 52 Statistical rezults of the whole region for alternative scenarios

			2020			2030		
			Case A	Case B	Case C	Case A	Case B	Case C
Average price of electricity		**EUR/ MWh**	21,565	20,627	14,479	19,778	18,749	13,126
Total electricity consumption		**TWh**	64,928	64,928	64,928	65,548	65,548	65,548
Peak load		**MW**	11994	11994	11994	12111	12111	12111
Net imports	**BA**	**TWh**	3,7008	3,0414	1,7599	-6,95	-4,15	-1,1
	ME	**TWh**	-1,881	-1,91	0,4667	-2,39	4,72	0,27
	RS	**TWh**	0,3716	3,1637	-0,31	4,698	4,72	0,25
	XK	**TWh**	1,8425	1,7876	1,603	1,27	1,9	0,58
	Total	**TWh**	3,3676	-	-	-3,37	-	-

The total installed capacities, sorted by the fuel type, are presented in Table 53. For the year 2020, in Cases A and B lignite has the highest share of total installed capacities and it amounts to 51,02%. Hydro accounted for 39,02%, wind accounted for 7,8%, gas accounted for 2,03% and sun accounted for 0,13%. In case C water has the highest share of total installed capacities and it amounts to 33,84%. Lignite accounted for 33,84%, wind accounted for 30,12%, gas accounted for 1,76% and sun accounted for 1,51%. Total capacity of all power plants in Case C is by some extent higher than the ones from cases A and B mainly because of new wind and solar capacities that in combination sum up to 20% of total installed capacity of the whole region.

For the year 2030, in Cases A and B lignite has retained the highest share of total installed capacities and it amounts to 55,25%. Hydro accounted for 33,76%, wind accounted for 7,3%, sun accounted for 2,02% and gas accounted for 1,66%. In case C water has the highest share of total installed capacities and it amounts to 31,95%. Lignite accounted for 30,86%, wind and sun accounted for 28,37% and gas accounted for 1,66%. Total capacity of all power plants in Case C is by some extent higher than the ones from cases A and B mainly because of new wind and solar capacities that in combination sum up to 20% of total installed capacity of the whole region.

Table 53 Total installed power by fuel type

Fuel type (MW)	Scenario 2020		Scenario 2030	
	Case A/B	**Case C**	**Case A/B**	**Case C**
LIG	8,865	6,565	11.755	6.565
GAS	353	353	353	353
WAT	6,780	6,780	7.183	6.797
WIN	1,355	6,036	1.554	6.036
SUN	23	303	430	6.036
Total	17,376	20,037	21.275	25787

Table 54 presents values of cross border flows within each country in the Wester Balkans region and cross border flows with the RoW, in case A for the year 2020 and 2030.Serbia has the highest values of imports and Bosnia and Herzegovina has the highest values of exports between the countries from the RoW. Montenegro has lowest value of both exports and imports between countries from the ROW. This is mainly because Montenegro is a country with lowest number of neighbouring countries. Within analysed countries, in the year 2020, maximal value of annual electricity exchange is recorded from Montenegro to Kosovo while the minimum value is recorded from Kosovo to Montenegro. In the year 2030, maximal value of annual electricity exchange is recorded from Bosnia and Herzegovina to Serbia while the minimum value is recorded from Kosovo to Montenegro.

Table 54 Cross border flows within simulated region in case A for the year 2020 and 2030

TO \ FROM		BA	ME	RS	XK	RoW	Total Import
BA	**2020**	-	1.225	1.732	-	223,84	3.180,79
	2030	-	1.753	1.234	-	224	3.211
ME	**2020**	1.168,05	-	1.276,11	264,04	129,04	2.837,24
	2030	1.621	-	2244	339	129	4.333
RS	**2020**	1.671,28	383	-	590,24	5.298,636	7.943,536
	2030	4.493	1.547	-	988	5299	12.327
XK	**2020**	-	2.577	1.657,16	-	608,71	4.842,92
	2030	-	2.891	1244	-	609	4.744
RoW	**2020**	4.042,21	532,	2.906,95	2.146,12	-	9.627,82
	2030	4.042	533	2.907	2.149	-	9.631
Total Export	**2020**	6.881,54	4.717,92	7572,22	3.000,4	6.260,226	-
	2030	1.0156	6.724	7.629	3.476	6.261	-

Table 55 shows values of cross border flows within each country in the Wester Balkans region in case B for the year 2020 and 2030. In this case, there is no exchange between the countries from the RoW. This is due to the fact that system in case B operate in an island regime. Within analysed countries, in both of the years maximal value of annual electricity exchange is recorded from Bosnia and Herzegovina to Serbia while the minimum value is recorded from Kosovo to Montenegro. Serbia has the highest values of total imports while Bosnia and Herzegovina has the highest values of total exports in both of the years. In the year 2030, cross border flows within each country is higher than in the year 2020. This is due to fact that total electricity demand is higer in the year 2030.

Table 55 Cross border flows within simulated region in case B for the year 2020 and 2030

TO \ FROM		BA	ME	RS	XK	RoW	Total Import
BA	**2.020**	-	1.000,289	672,3749	-	-	1.672,66
	2.030	-	1.638	1048	-	-	2.686
ME	**2.020**	1.306,747	-	970,97	220,8108	-	2.498,53
	2.030	1.667	-	1.894	441	-	4.002
RS	**2.020**	3.407,353	586,2548	-	1.506,664	-	5.500,27
	2.030	5.163	1.934	-	1.471	-	8.568
XK	**2.020**	-	2.821,904	693,217	-	-	3.515,12
	2.030	-	2.901	907	-	-	3.808
RoW	**2.020**	-	-	-	-	-	-
	2.030	-	-	-	-	-	-
Total Export	**2.020**	4.714,1	4.408,45	2.336,56	1.727,48	-	-
	2.030	6.830	6.473	3.849	1.912	-	-

Table 56 presents values of cross border flows within each country in the Wester Balkans region and cross border flows with the RoW, in case C for the year 2020 and 2030. As said before there is no exchange between the countries from the RoW because system in case C operate in an island regime. Within analysed countries, in the year 2020, maximal value of annual electricity exchange is recorded from Montenegro to Kosovo while the minimum value is recorded from Montenegro to Serbia. In the year 2030, maximal value of annual electricity exchange is recorded from Serbia to Montenegro while the minimum value is recorded from Kosovo to Montenegro. Serbia has the highest values of total imports and exports in both of the years. Case C is scenario with the higest share of RES in total installed capacities, because of that solar irradiation and wind has significant impact on cross border flows. This is why cross border flows in the year 2020 differ substaintally from the year 2030.

Table 56 Cross border flows within simulated region in case C for the year 2020 and 2030

TO \ FROM		BA	ME	RS	XK	RoW	Total Import
BA	**2020**	-	693,32	1.440,3	-	-	2.133,62
	2030	-	1.801	2.030	-	-	3.831
ME	**2020**	1.788,087	-	1.320,145	569,97	-	3.678,2
	2030	1.608	-	3.592	503	-	4.095
RS	**2020**	2.105,41	383,43	-	1.265,05	-	3.753,9
	2030	3.320	935	-	2.357	-	6.612
XK	**2020**	-	2.134,74	1.303,36	-	-	3.438,1
	2030	-	2.696	740	-	-	3.436
RoW	**2020**	-	-	-	-	-	-
	2030	-	-	-	-	-	-
Total Export	**2020**	3.893,5	3.211,5	4.063,8	1.835,02	-	
	2030	4.928	5.432	6.362	2.860	-	

Electricity production by technology can be seen in Table 57 for all three scenarios in the year of the 2020 and 2030.

Table 57 Electricity production in alternative scenarios

Unit	Zone		2020			2030		
			Case A	Case B	Case C	Case A	Case B	Case C
Thermal power plants	BA	GWh	8.767	8.106	4.727	11.971	9.168	4.147
	ME		3.040	3.064	206	3.309	3.472	288
	RS		20.051	17.278	14.490	14.036	13.935	13.202
	XK		5.282	5.223	4.175	5.082	4.468	3.934
Hydropower plants	BA	GWh	9.936	9.937	9.927	10.418	10.429	8.484
	ME		2.768	2.773	2.762	2.782	2.790	2.316
	RS		15.522	15.503	15.514	17.320	17.322	12.740
	XK		205	205	204	219	219	205
Solar power plants	BA	GWh	-	-	96	-	-	1.896
	ME		15	15	24	46	46	561
	RS		13	13	222	261	261	4.267
	XK		3,75	3,75	44	250	250	1.015
Wind power plants	BA	GWh	1.106	1.106	3124	1.107	1.107	3.125
	ME		346	346	829,96	435	435	833
	RS		1.100	1.100	7179,7	1.320	1.320	7.199
	XK		249	249	1441,7	357	357	1.449
RES share		%	4,14	4,37	19,95	5,48	5,76	30,97

For both of the years, in Case A dominant technologies are coal and hydro with a small amount of wind and solar. Furthermore, the electricity produced from wind and solar is equal in cases A and B. Countries such as Bosnia and Herzegovina, Serbia and Kosovo all have lower electricity production from thermal power plants in Case B then in Case A. On the other hand Montenegro has higher electricity production from thermal power plants in Case B then in Case A. The lowest values of electricity production from thermal power plants are in Case C. This is because this is a scenario with lowest amount of thermal power plants and highest share of installed renewable energy sources. In the year 2020 the electricity production from hydropower plants doesnt differ substantially within all three scenarios, which proves that electricity production from hydropower plants is highly dependent on river hydrology. Lower production from hydropower plants in Case C for the year 2030 occurs due to reduced total installed capacities which can be seen in Table 53.

The electricity production fuel mixes for each country, and for all three scenarios are illustrated in Figure 54. The legend on the right also shows a colour scheme representing certain fuel types. For example wind is marked red and sun yellow while other colours are the same as in reference scenario.

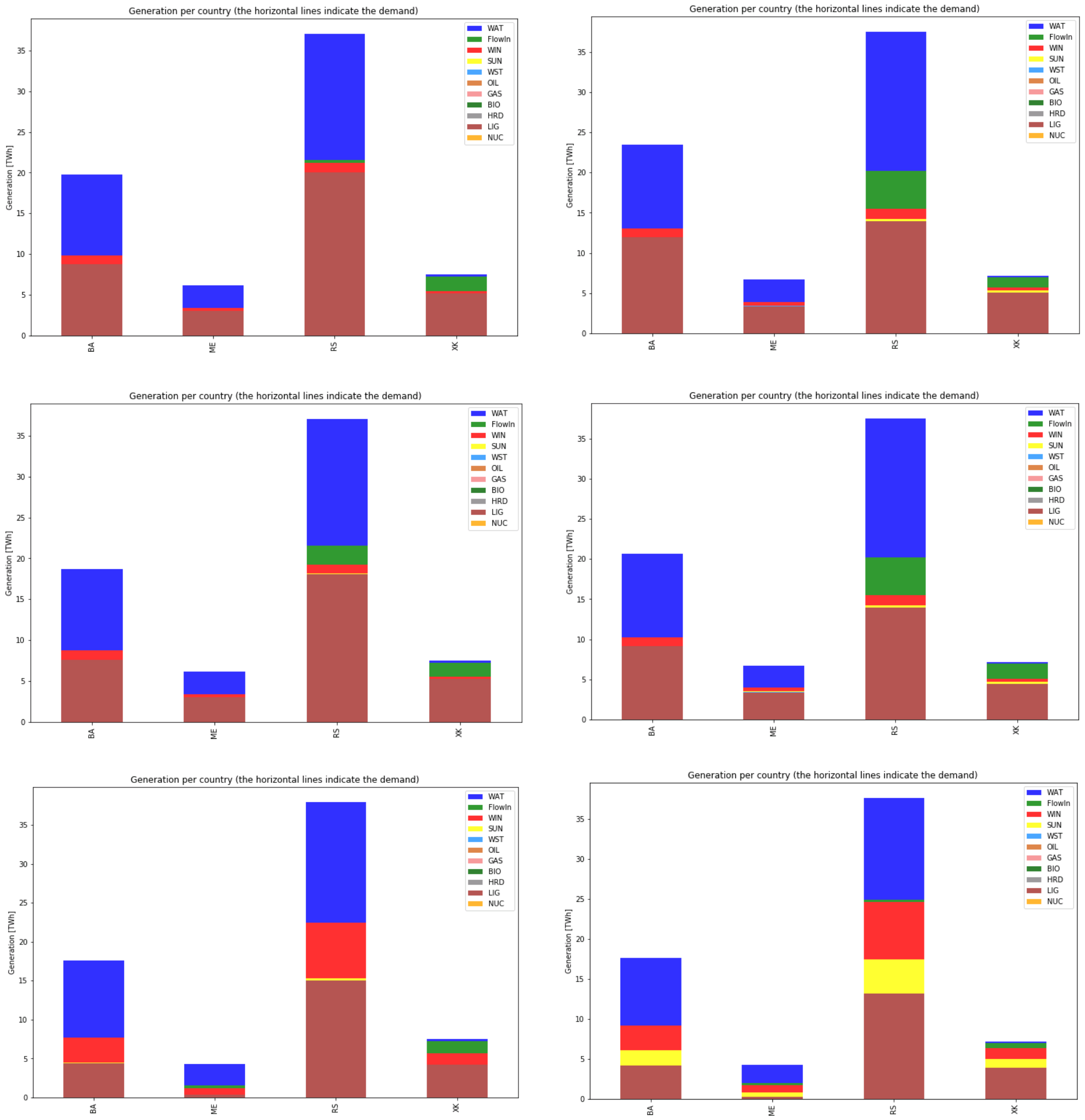

Figure 54 Fuel mix in electricity production for case A (top), case B (middle) and case C (bottom) for the year 2020 (left column) and 2030 (right column)

The total electricity production in Case A ammounts to 68,41 TWh for the year 2020, and 68,92 for the year 2030. Thermal power plants account to 54,29% for the year 2020, and 49,92% for the year 2030. Hydropower plants account to 41,56% for the year 2020, and 44,61% for the year 2030. Solar power plants account to 0,47% for the year 2020, and 2,41% for the year 2030. Wind power plants account to 4,1% for the year 2020, and 3,06% for the year 2030. In the Case B electricity production ammounts to 64,93 TWh for the year 2020, and 65,55 TWh for the year 2030. Shares of fuel technology in total production are similar to those from Case A, for both of the years. The reason for that is the identical amount of installed power capacities in both cases. The drop in electricity production in Case B occurs because there is no export of electricity to the RoW. Instead of exporting the electricity produced from local thermal power plants there are shut down and excluded from production. This is the reason why Serbia has an increasee of electricity importations in Case B than in Case A. Furthermore unfavourable operating parametars of thermal power plants also reduce the total production of Serbia. The Case C has similar electricity production to the Case B where it ammounts to 64,971 TWh for the year 2020, and 65,65 TWh for the year 2030. This is due to the fact that both systems operate in an island regime. Share of electricity produced by thermal power plants in case C is 36,32% for the year 2020, and 32,86% for the year 2030. Hydropower plants account to 43,73% for the year 2020, and 36,17% in the year 2030. Share of RES for the year 2020 is 19,95%, of whitch wind ammounts to 19,35% and solar to 0,6%. RES share for the year 2030 is 28,1%, of whitch wind ammounts to 13,66% and solar to 14,42%. Higher share of RES is due to increased installed capacities in Case C compared to the other two cases. From the fuel mixes it can be seen that electricity production in Case C has the highest production from RES in all four countries. In the year 2020 solar power plants are producing electricity in al four countries, but it is difficult to destingusih it on the diagrams mainly because of small amount of electricity they produce in comparison to other power plants.

5.2.2. Montenegro

The Power dispatch curve in Case B for the year 2020 is shown in Figure 55. From there it is clear that most of the demand is covered by thermal power plants. The electricity production from wind and hydropower plants is higher in January. Figure 56 shows the power dispatch curve in case C for the year 2020. Fromthere it can be seen that most of demand is covered by RES while the rest is imported. It is also clear that export is in direct correlation with hydropower production. The thermal power plant from the Case C in the year 2020 was in operation only from mid-February till the beginning of April. The difference between Cases B and C is that case C has higher RES production. Figure 57 illustrates the power dispatch curve for the Case B for the year 2030. From there it is clear that lignite fired thermal power plants have high electricity production during the whole year. The export is higher in July than in January mainly due to the higher production of solar power plants during the summer. Figure 58 represents the power dispach curve for the Case C in the year 2030. This is a scenario with the higest share of RES in the total mix.. The power dispatch curve in Case C differs from the one from the Case Bmainly because of higher penetration of RES. Furthermore, most of demand from the Case C is covered only by RES. The main diference between the years 2020 and 2030 is that, beside higer electricity demand in 2030, in the later one total share of RES is higher. Moreover, it is also clear that during most of the year, Montenegro exports electricity. In all cases solar power plants have higher production during spring and summer due to the higher Solar insulation during that period. The highest production from wind power plants occours between the mid ofSeptember and mid ofMay mainly due to the high amount of wind in those periods. Regarding the river hydrology, run of river hydropower plants worked at nominal power during winter and spring, when there is a lot of percitipation. The Case C is an example of how Montenegrian power system could look like if there is high amount of intermittent energy sources installed. Reservoir level curve is the same for all three cases and it follows reservoir levels of accumulation hydropower plants that are given as input data to model.

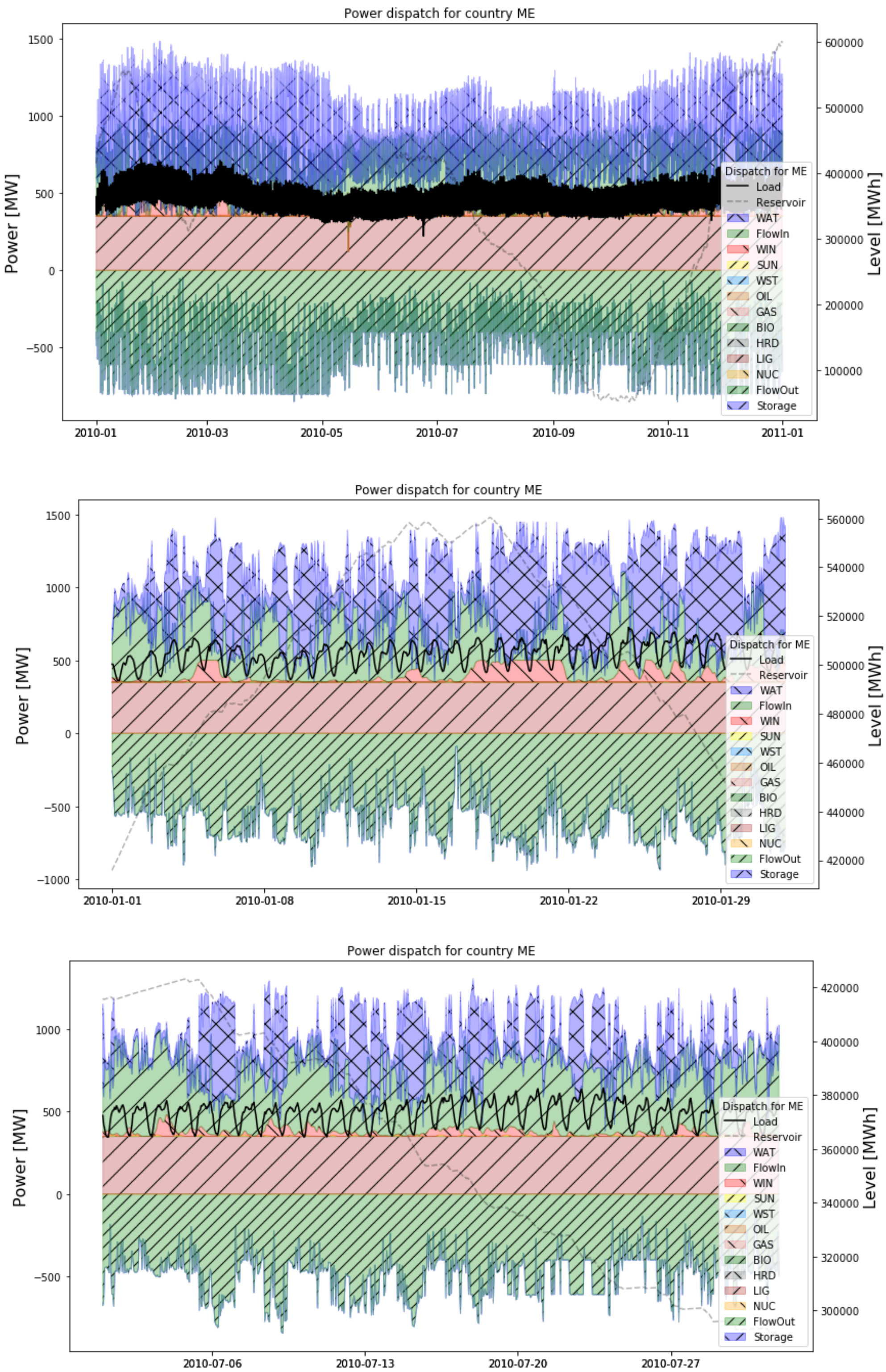

Figure 55 Power dispatch curve in the case B for the year 2020 of Montenegro for whole year (top), January (middle) and July (bottom)

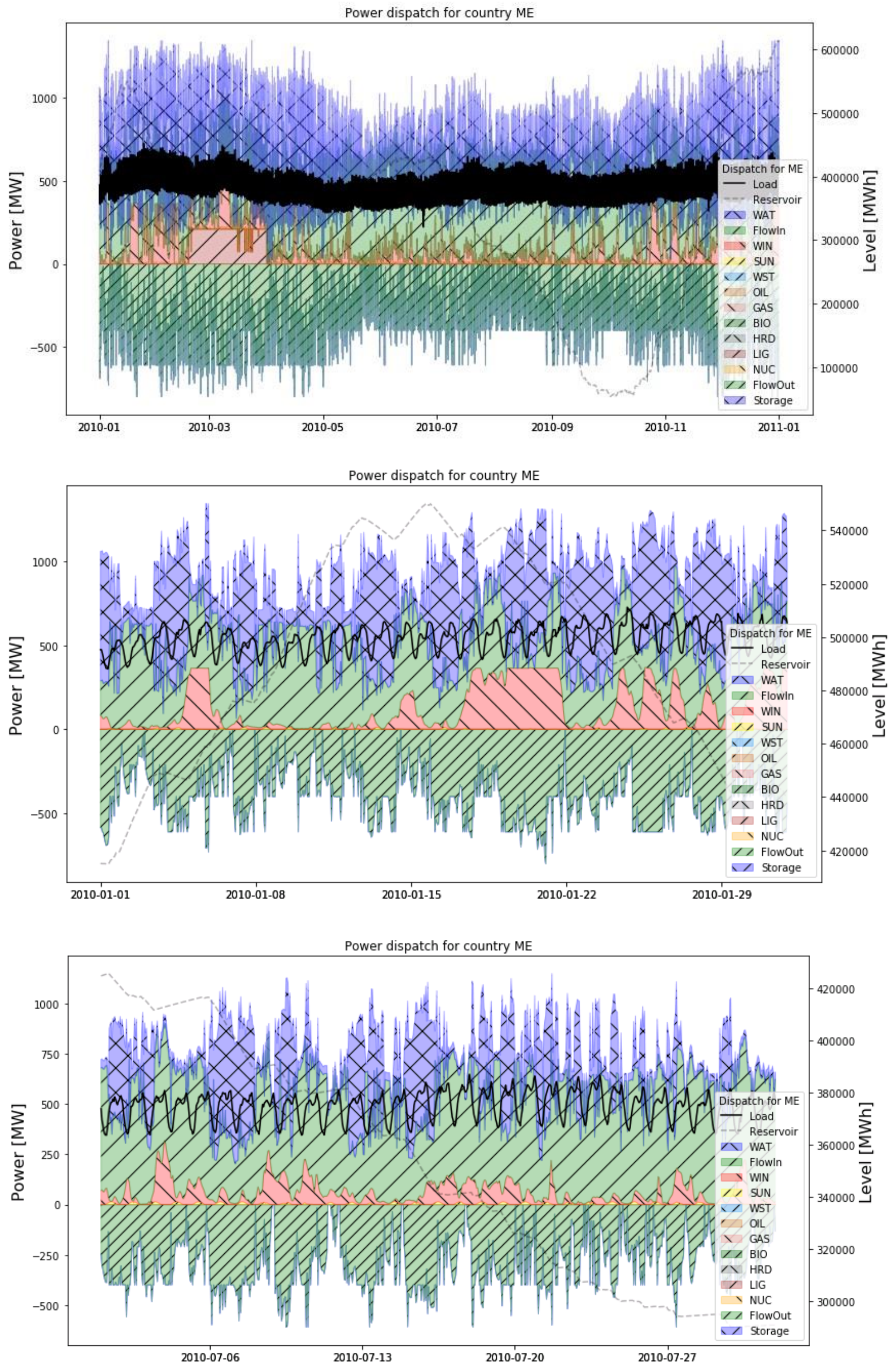

Figure 56 Power dispatch curve in the case C for the year 2020 of Montenegro for whole year (top), January (middle) and July (bottom)

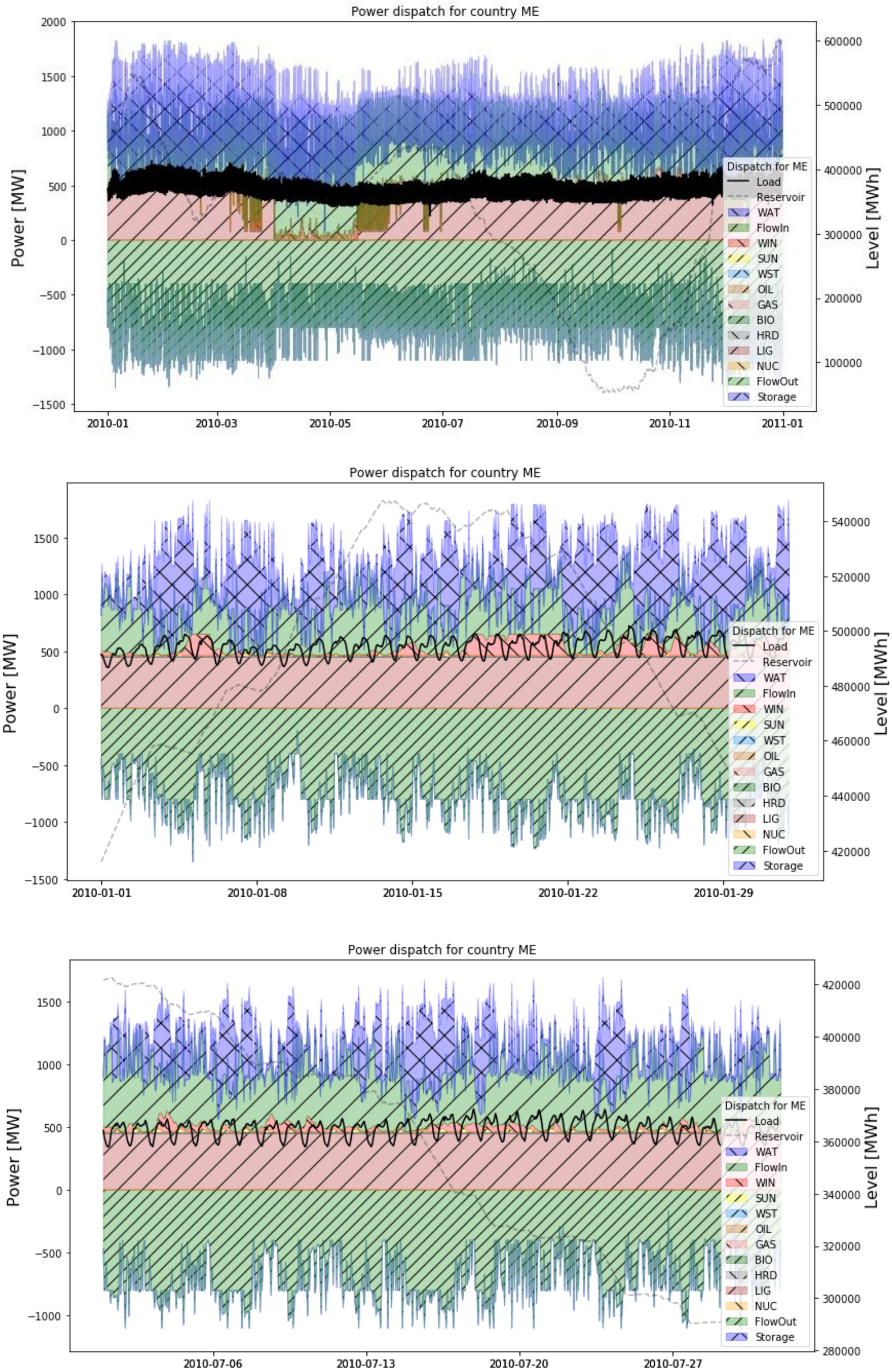

Figure 57 Power dispatch curve in the case B for the year 2030 of Montenegro for whole year (top), January (middle) and July (bottom)

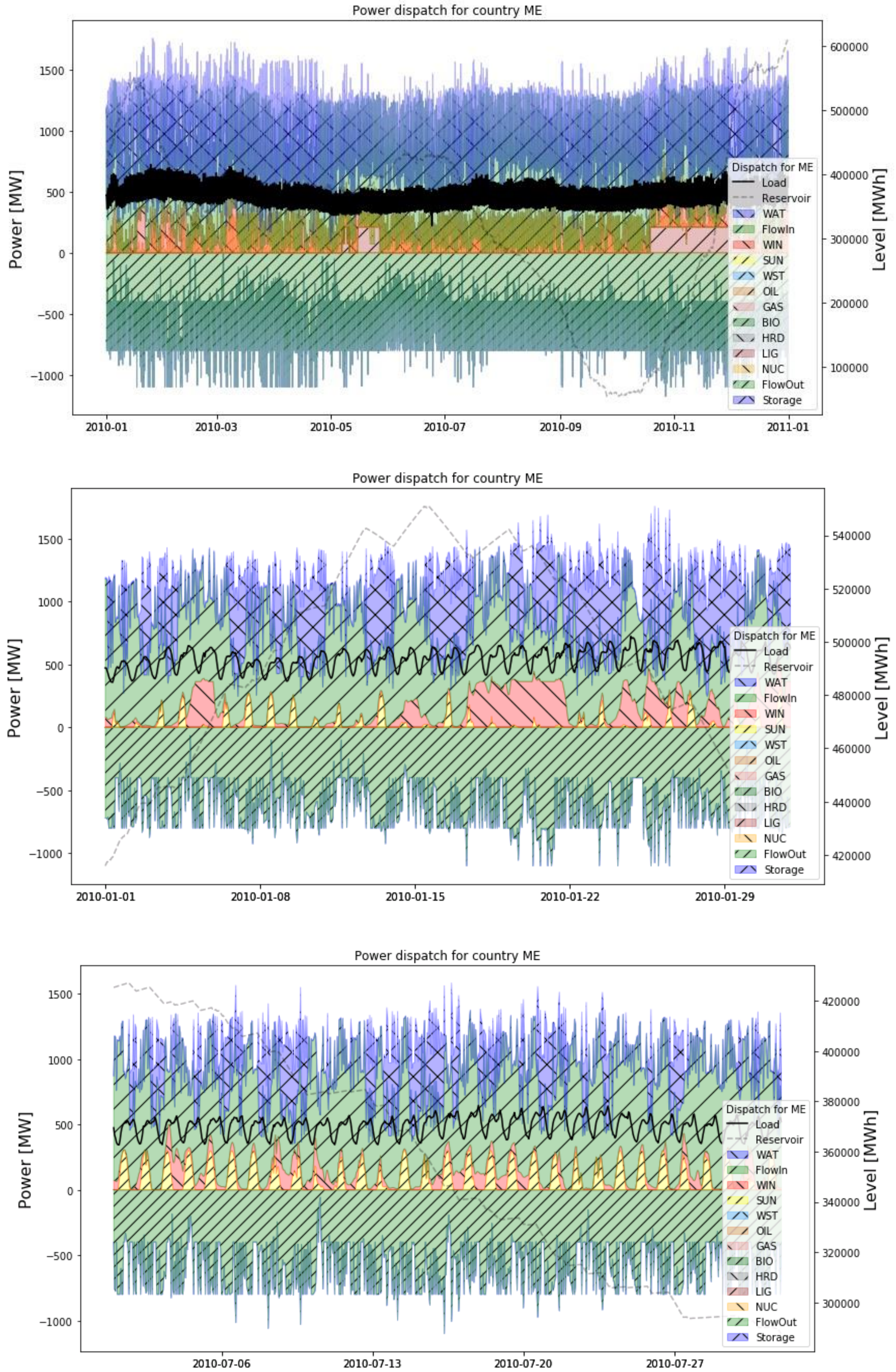

Figure 58 Power dispatch curve in the case C for the year 2030 of Montenegro for whole year (top), January (middle) and July (bottom)

5.2.3. Bosnia and Herzegovina

The power dispatch curve in case B for the year 2020 is presented in Figure 59. From there it is clear that most of demand is covered by thermal and hydropower plants. The electricity production from wind and hydropower plants is higher in January. Figure 60 shows the power dispatch curve in case C for the year 2020. From there it can be seen that compared to case B, Case C has higher share of RES in electricity production. It is also clear that in both January and July, production from wind exceeds production from the thermal power plants. Bosnia and Herzegovina has significant amount of installed hydropower plants in cases A and B and because of that thermal power plants doesnt work as typical baseload plants. The difference between cases B and C is that case C has higher RES production. Figure 61 illustrates the power dispatch curve in case B for the year 2030. From there it is clear that coal fired thermal power plants has more fluctuating trend than in 2020. Moreover, it can be seen that Bosnia and Herzegovina's electricity export is proportional to hydropower production. Figure 62 represents the power dispach curve for case C in 2030. This is scenario with the higest share of RES in the total mix. Furthermore, significant amount of electricity is produced from solar power plants while production of coal fired thermal power plants is degraded to minimum. The power dispatch curve in Case C differs from the one from the Case B mainly because of higher penetration of RES. Furthermore, most of demand from the case C is covered by RES. The main diference between the years 2020 and 2030 is that, beside higer electricity demand in 2030, in the later one total share of RES, export and import is higher. In all cases solar power plants have higher production during spring and summer due to the higher Solar insulation during that period. The highest production from wind power plants occours between the mid of September and mid of May mainly due to the high amount of wind in those periods. Run of river hydropower plants worked at nominal power in periods during winter and spring when there is lot of rainfalls. The Case C is example of how power system could look like with high amount of intermittent energy sources installed. Reservoir level curve is the same for all three cases and it follows reservoir levels of accumulation hydropower plants that are given as input data to model.

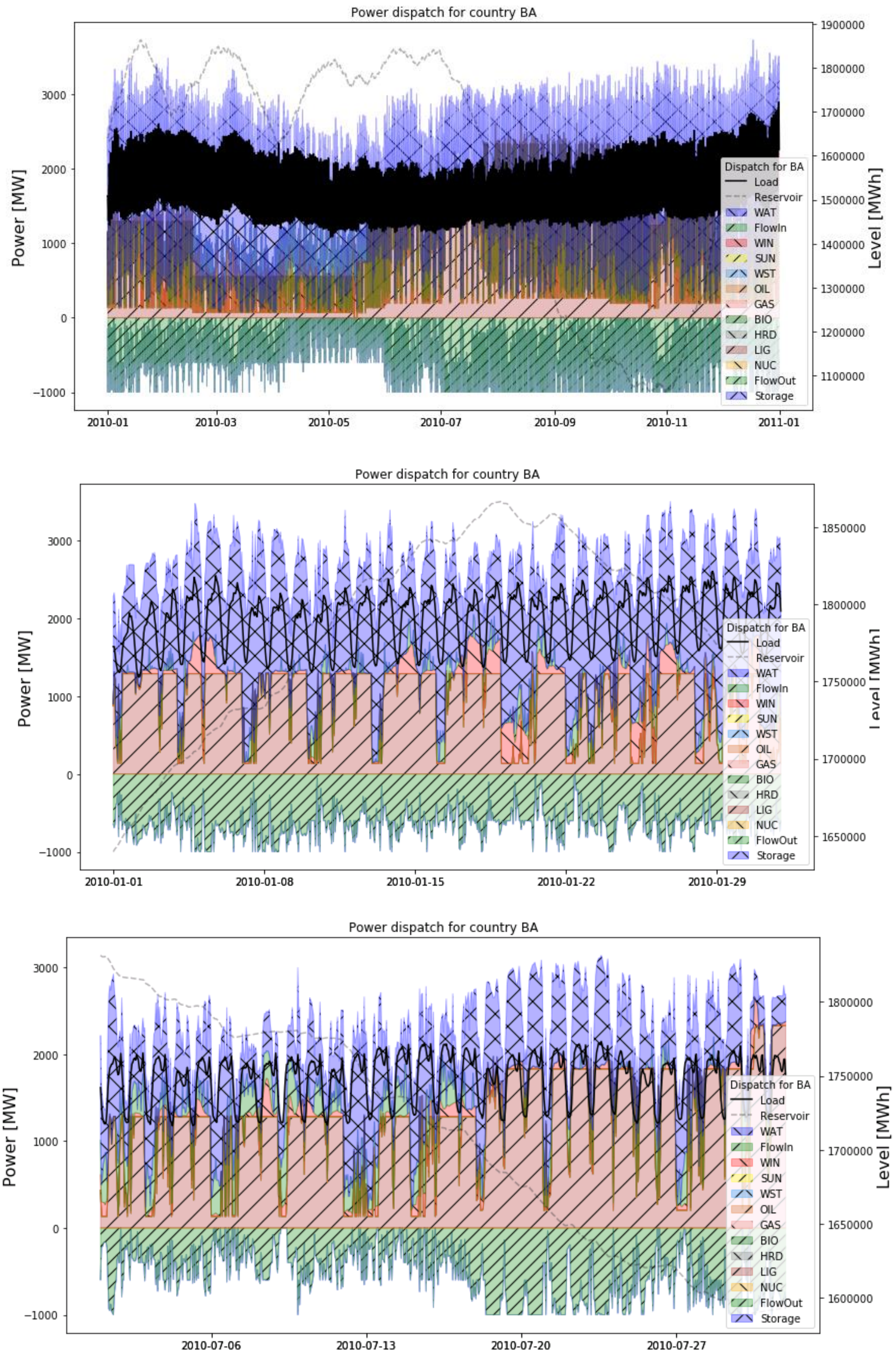

Figure 59 Power dispatch curve in the case B for the year 2020 of Bosnia and Herzegovina for whole year (top), January (middle) and July (bottom)

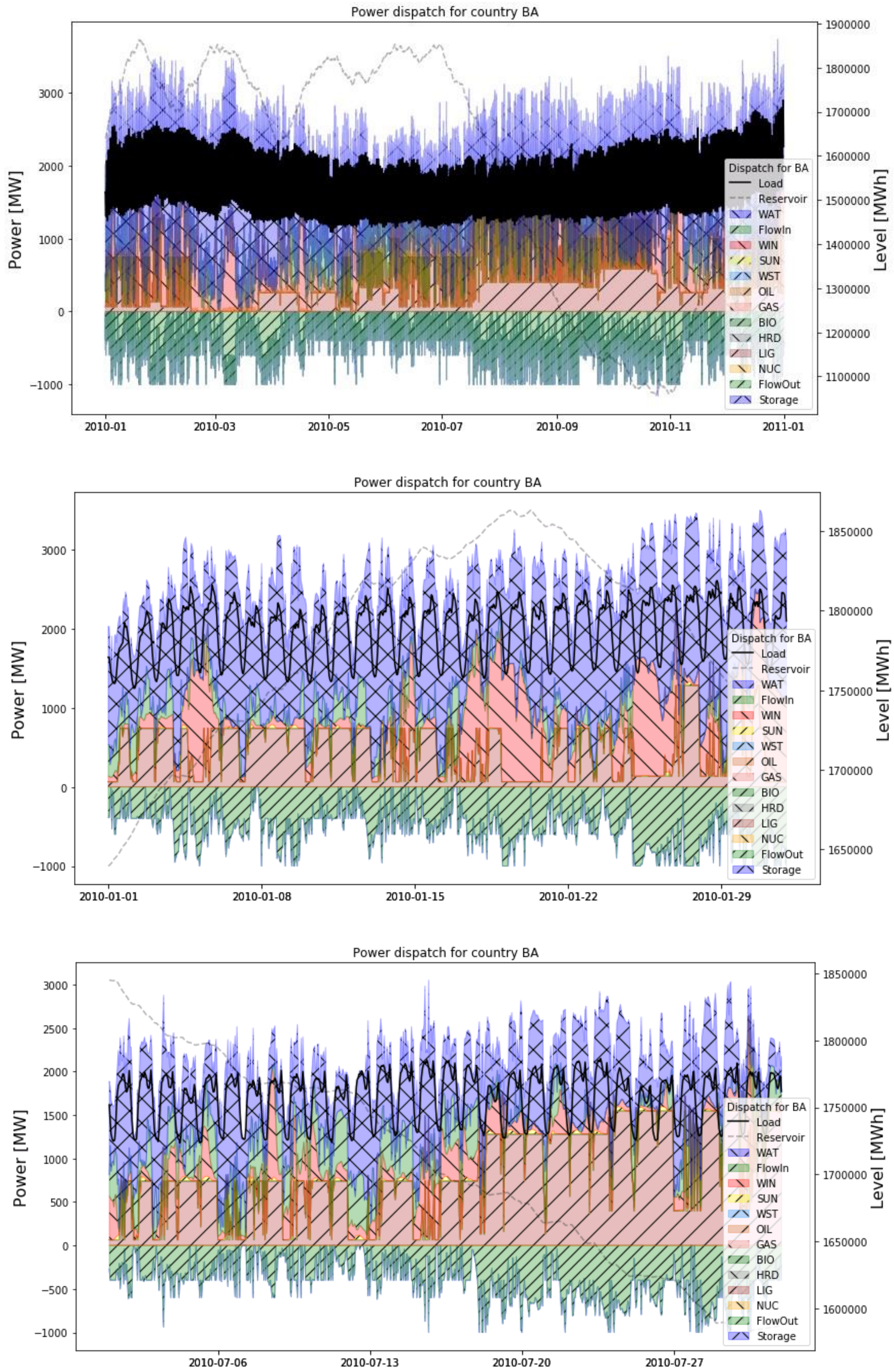

Figure 60 Power dispatch curve in the case C for the year 2020 of Bosnia and Herzegovina for whole year (top), January (middle) and July (bottom)

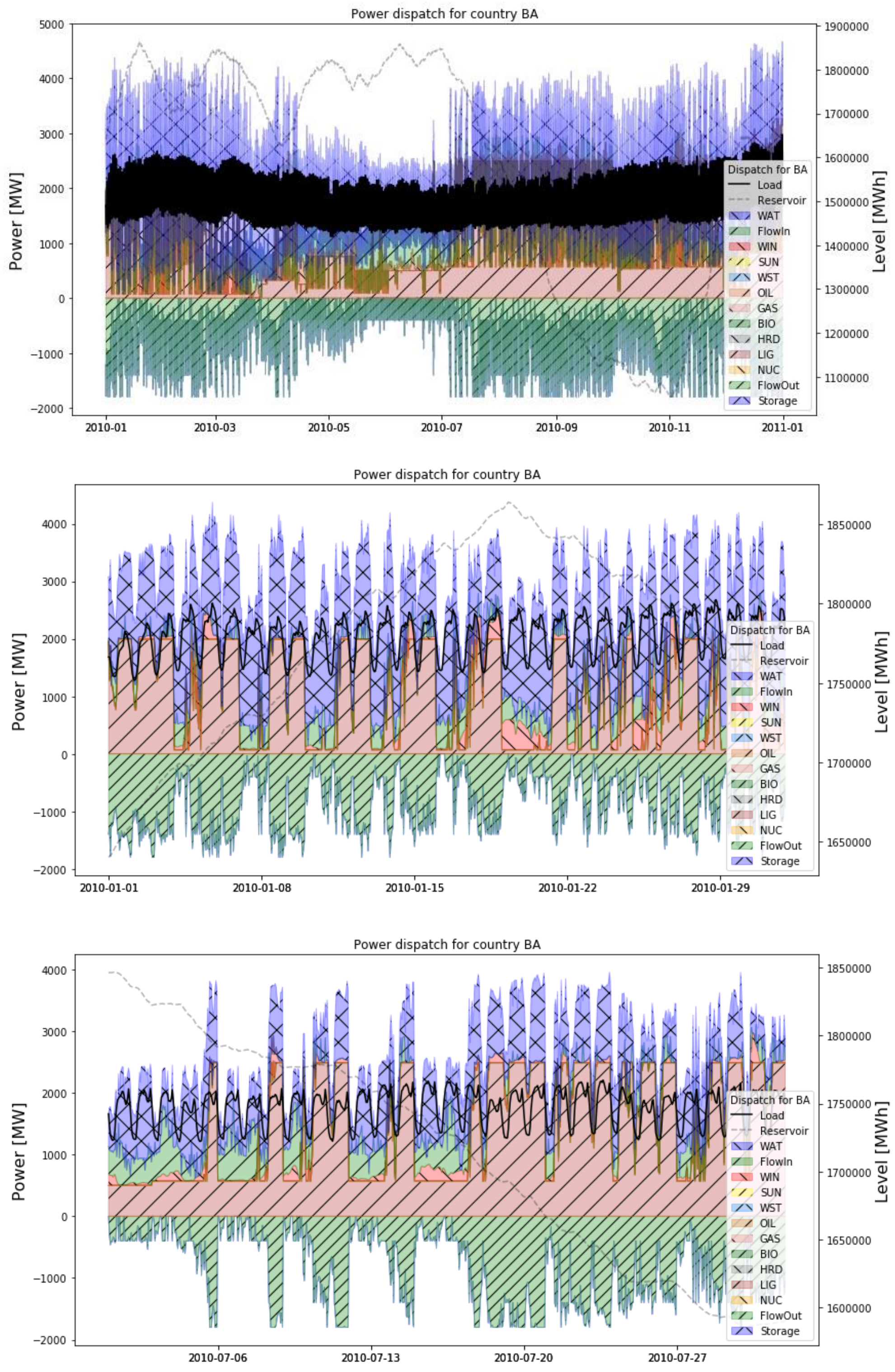

Figure 61 Power dispatch curve in the case B for the year 2030 of Bosnia and Herzegovina for whole year (top), January (middle) and July (bottom)

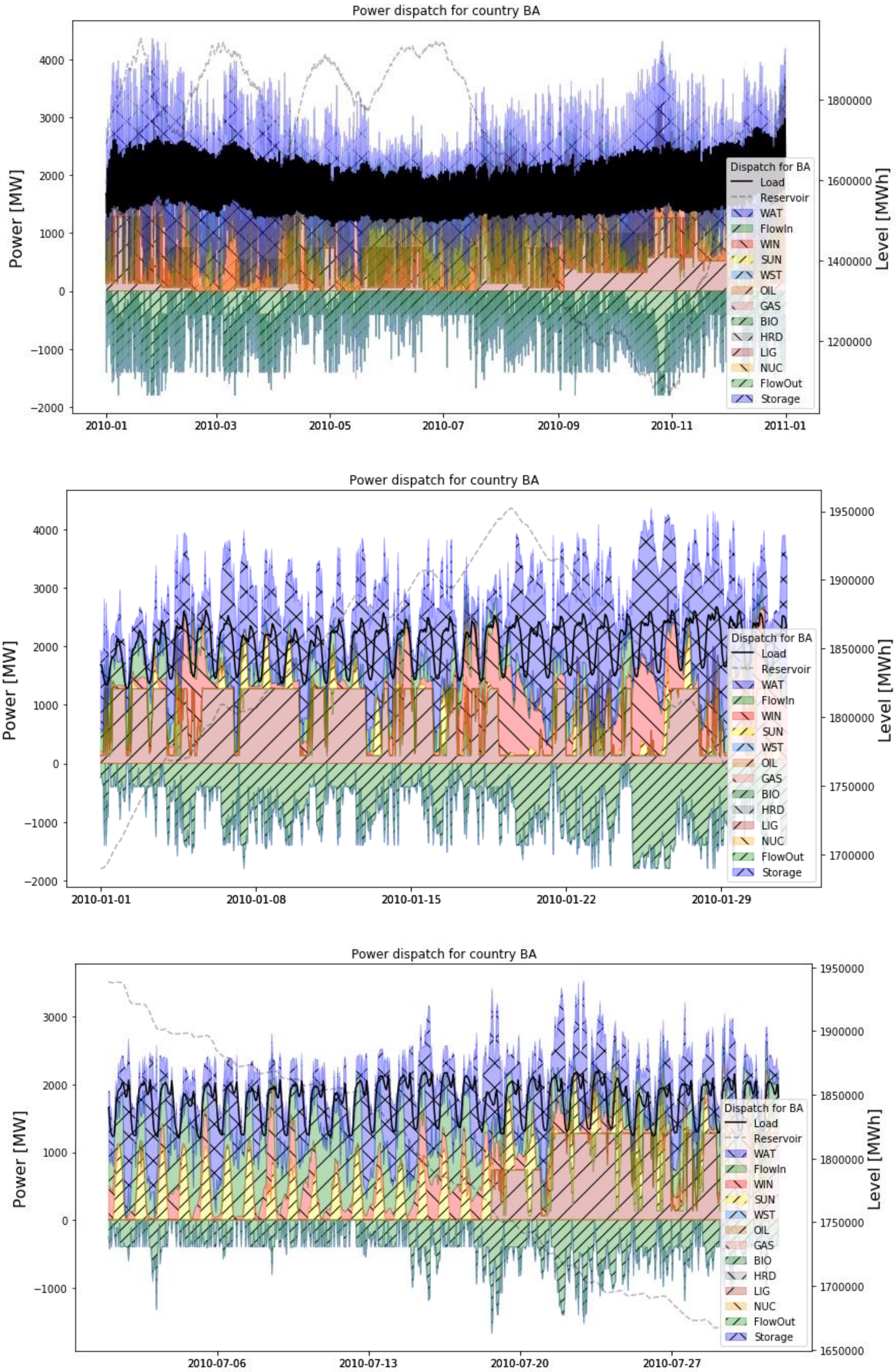

Figure 62 Power dispatch curve in the case C for the year 2030 of Bosnia and Herzegovina for whole year (top), January (middle) and July (bottom)

5.2.4. Serbia

The power dispatch curve in Case B for the year 2020 is presented in Figure 63. From there it is clear that most of the demand is covered by coal fired thermal and hydropower plants. The Export and Import values are low in both January and July. This leads to great potential for Serbia to operate in an island regime. Figure 64 shows the power dispatch curve in Case C for the year 2030. From there it can be seen higher share of RES in electricity production compared to case B. Furthermore, it is important to point that in some days total electricity demand could be covered by only wind and solar. Serbia has significant amount of installed hydropower plants in Case C and because of that lignite fired thermal power plants doesnt work as typical baseload plants. The difference between Cases B and C is that case C has higher RES production. Figure 65 illustrates the power dispatch curve for the Case B in the year 2030. From there it is clear that lignite fired thermal power plants has high electricity production during the whole year. The higest electricity production from lignite fired thermal power plants occurs in the case B. Figure 66 represents the power dispach curve in case C for the year 2030. This is scenario with the higest share of RES in the total mix. Furthermore, significant amount of electricity is produced from solar power plants while production of coal fired thermal power plants is degraded to minimum. The power dispatch curve in Case C differs from one from the Case B, mainly because of higher penetration of RES. Moreover, most of demand from the Case C is covered by RES. The main diference between the years 2020 and 2030 is that, beside higer electricity demand in 2030, in the later one total share of RES, export and import is higher. In all cases solar power plants has higher production during spring and summer because of better insulation during that period. The highest production from wind power plants occours between the mid of September and mid of May mainly due to the high amount of wind in those periods. Regarding to river hydrology, run of river hydropower plants worked at nominal power during winter and spring, when there is a lot of percitipation. The Case C is example of how power system could look like if there is high amount of intermittent energy sources installed. Reservoir level curve is same for all three cases and it follows reservoir levels of accumulation hydropower plants that are given as input data to model.

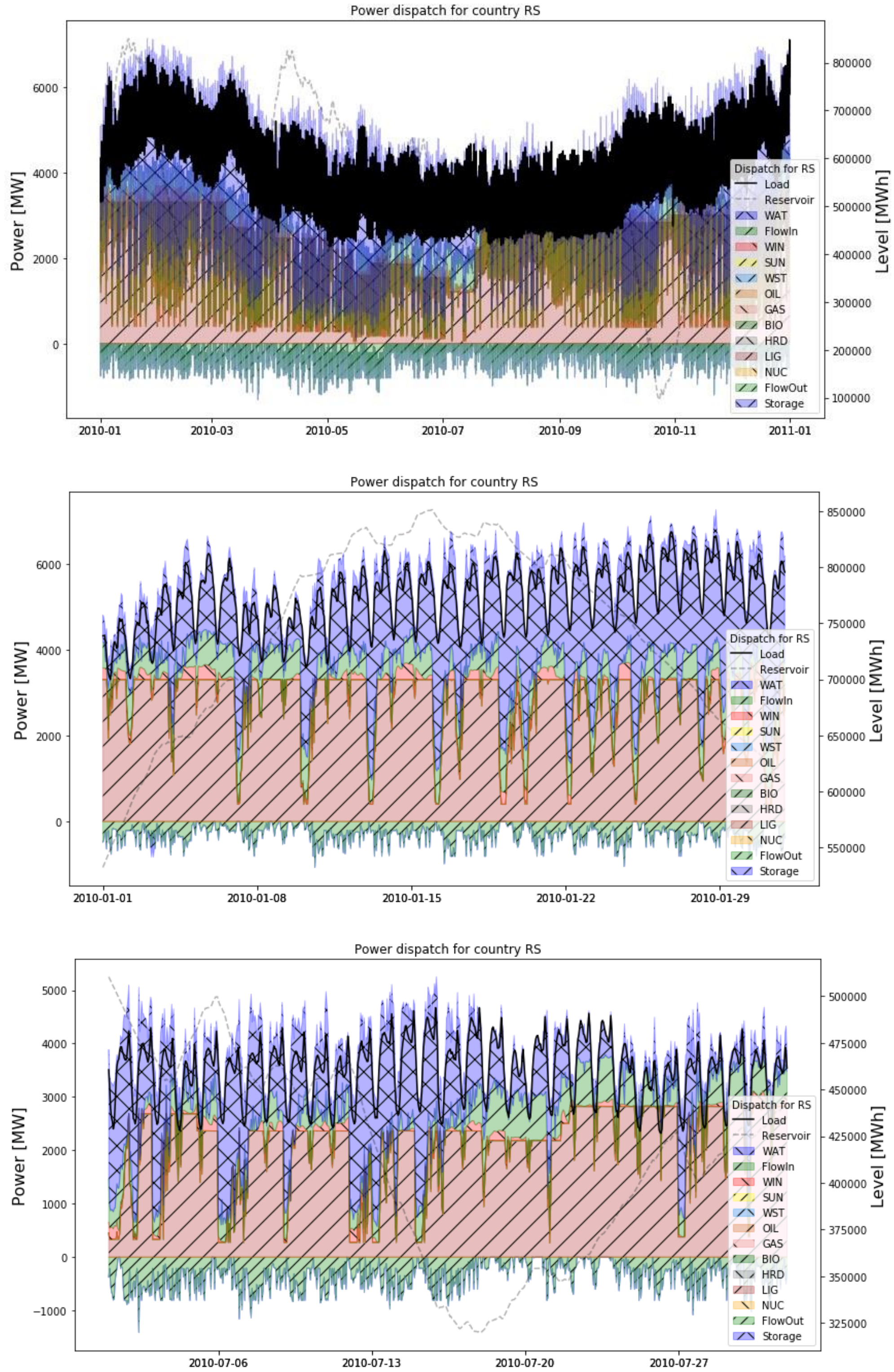

Figure 63 Power dispatch curve in the case B for the year 2020 of Serbia for whole year (top), January (middle) and July (bottom)

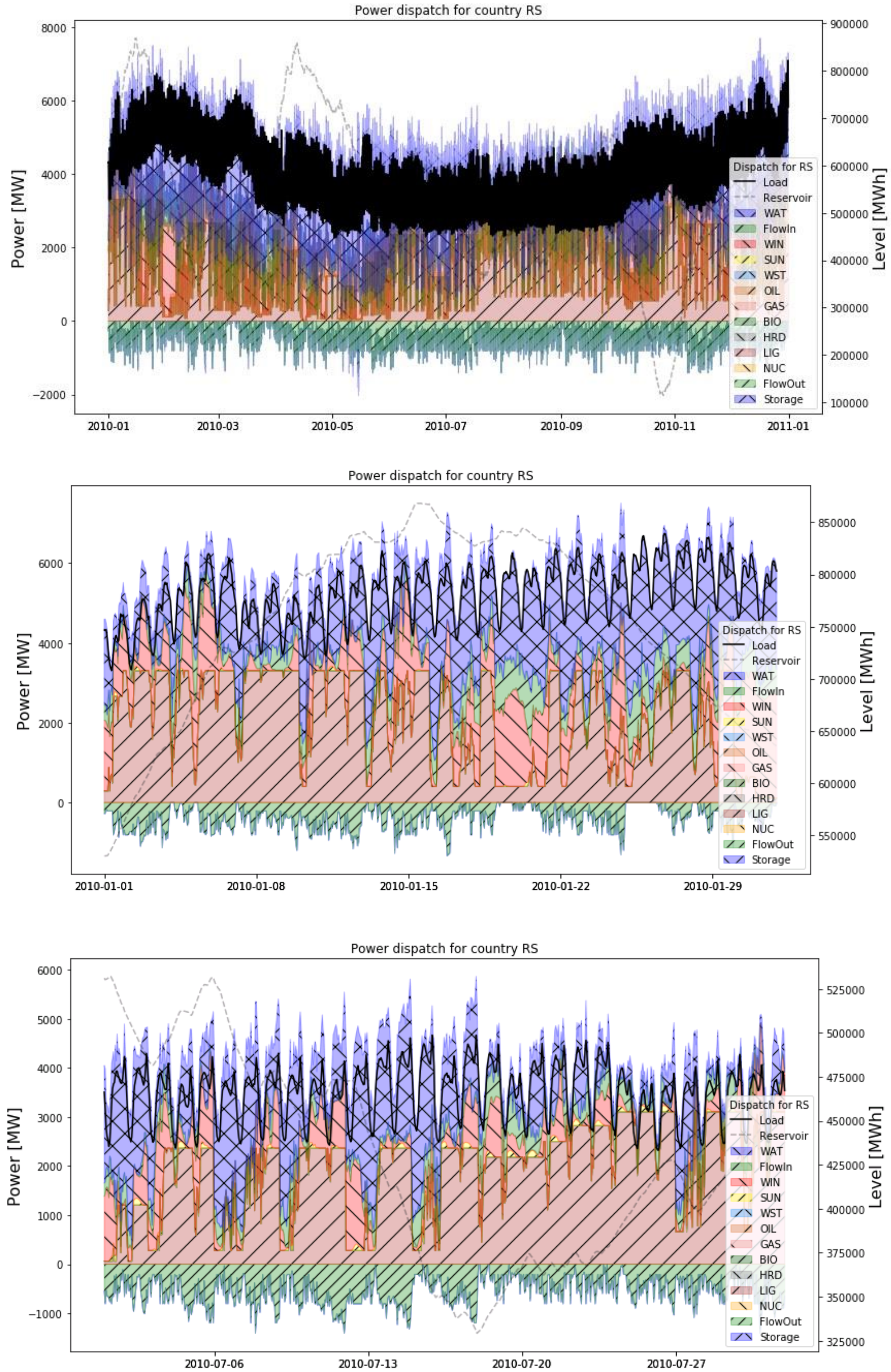

Figure 64 Power dispatch curve in the case C for the year 2020 of Serbia for whole year (top), January (middle) and July (bottom)

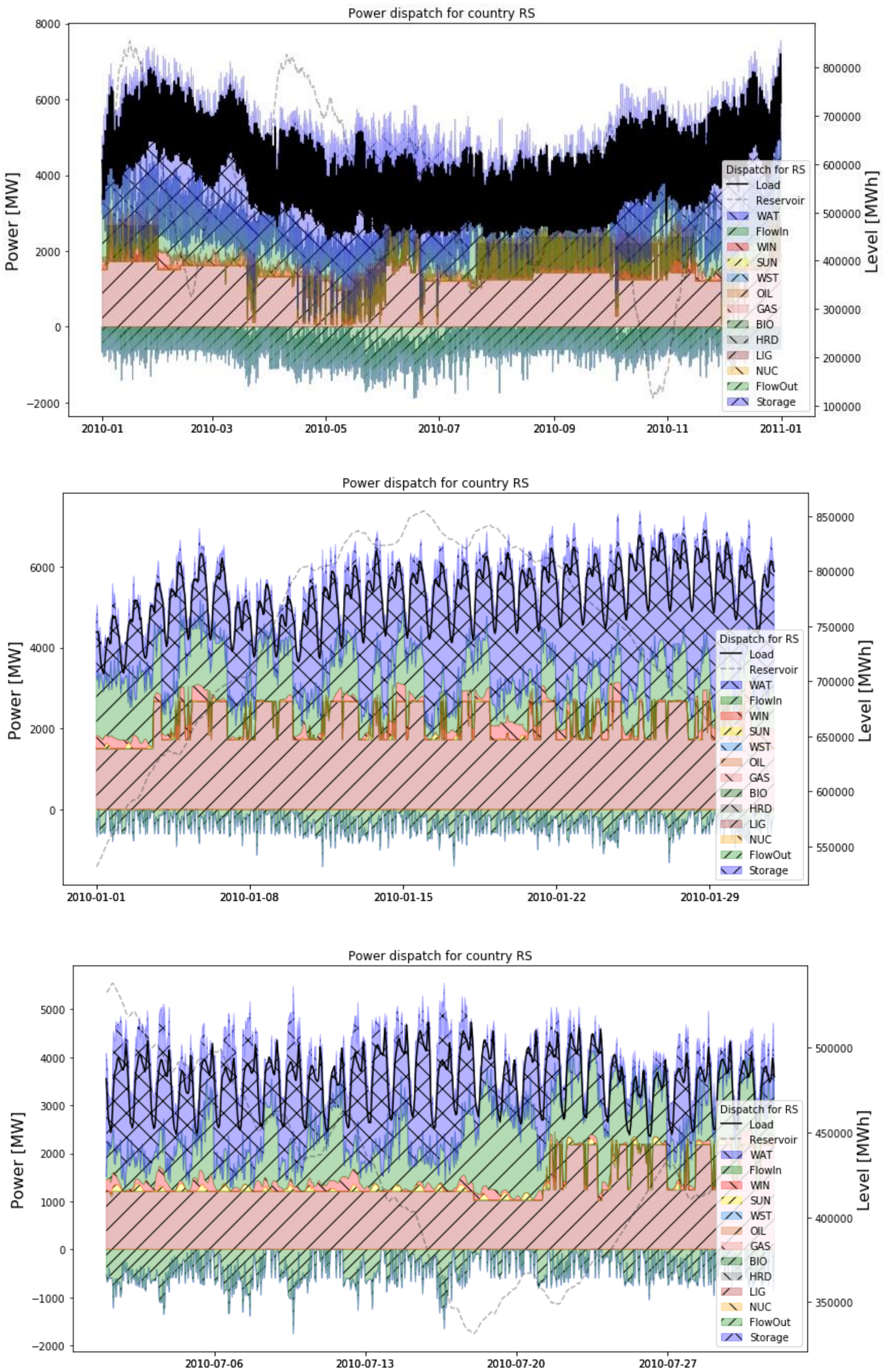

Figure 65 Power dispatch curve in the case B for the year 2030 of Serbia for whole year (top), January (middle) and July (bottom)

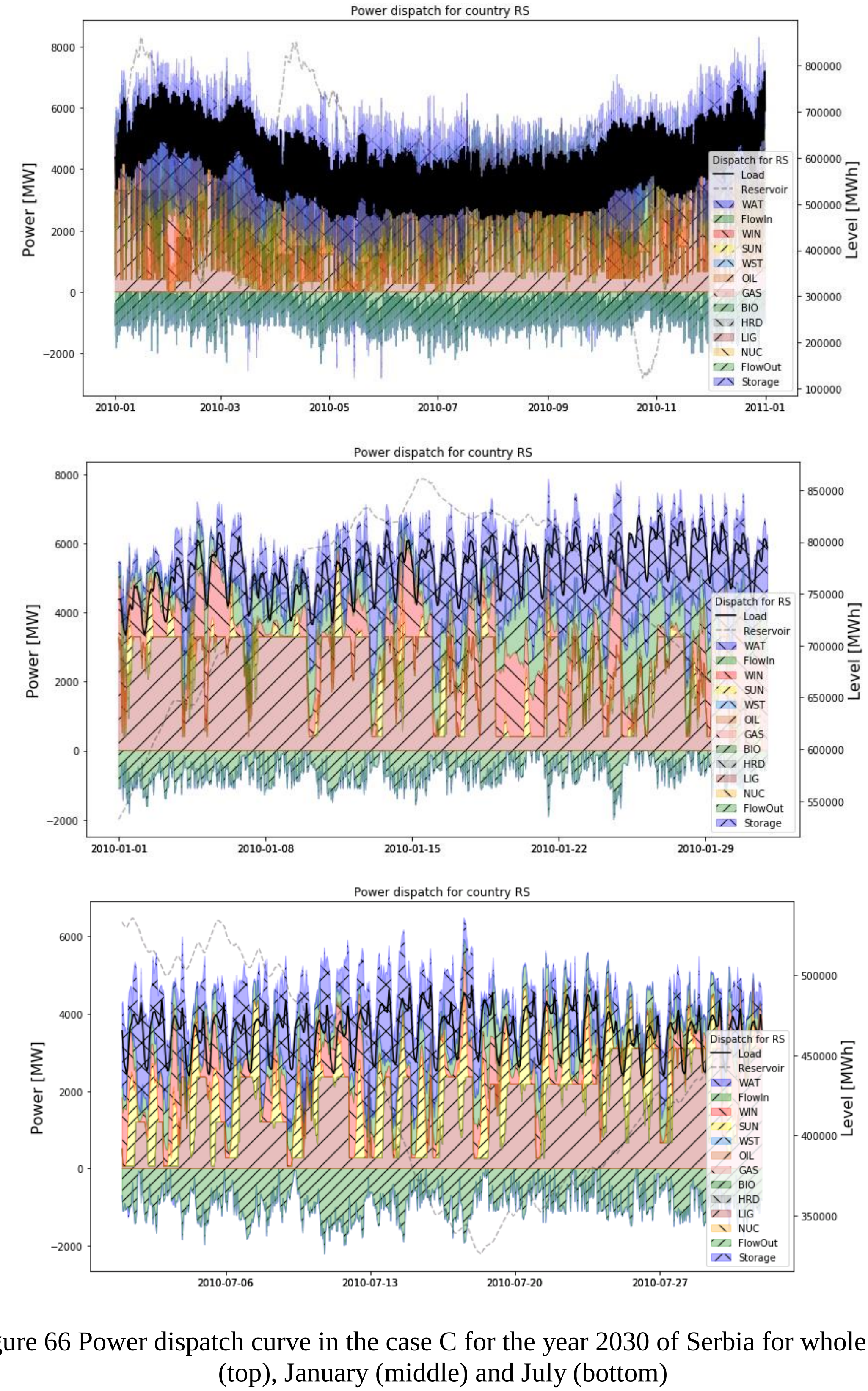

Figure 66 Power dispatch curve in the case C for the year 2030 of Serbia for whole year (top), January (middle) and July (bottom)

5.2.5. Kosovo

The Power dispatch curve in Case B for the year 2020 is shown in Figure 67. From there it is clear that most of demand is covered by lignite fired thermal power plants. Figure 68 shows the power dispatch curve in Case C for the year 2030. From there it can be seen that even in a high RES scenario there is significant production from thermal power plants. The lignite fired thermal power plants in Kosovo operate during the whole year, and they are shut down only for planned outages. The difference between Cases B and C is that case C has higher import and export. Figure 69 illustrates the power dispatch curve for in Case B for the yeaer 2030. From there it is clear that lignite fired thermal power plants has high electricity production during the whole year. The solar power plants has higher production in July due to higher solar insulation during that period. Figure 70 represents the power dispatch curve for Case C in the year 2030. This is a scenario with the higest share of RES in the total mix. Furthermore, it can be seen that wind power plants plants has higher production in January than in July mainly due to the high amount of wind in January. Moreover, most of demand in case C is covered by lignite fired thermal power plants. The main diference between the years 2020 and 2030 is that, beside higer electricity demand in 2030, in the later one total share of RES, export and import is higher. Regarding to river hydrology, run of river hydropower plants worked at nominal power in periods during winter and spring due to high percitipations. Reservoir level curve is same for all three cases and it follows reservoir levels of accumulation hydropower plants that are given as input data to model.

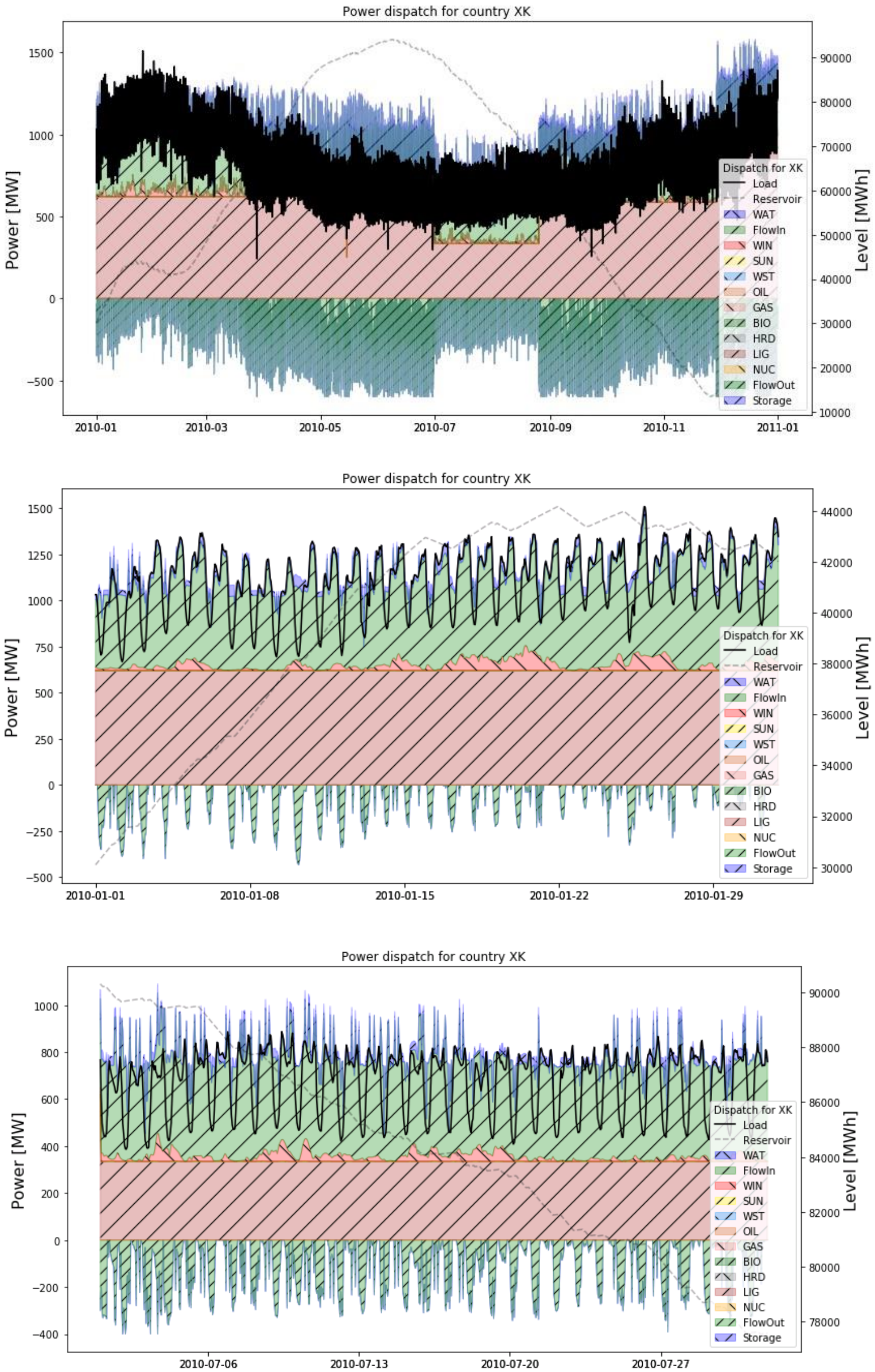

Figure 67 Power dispatch curve in the case B for the year 2020 of Kosovo for whole year (top), January (middle) and July (bottom)

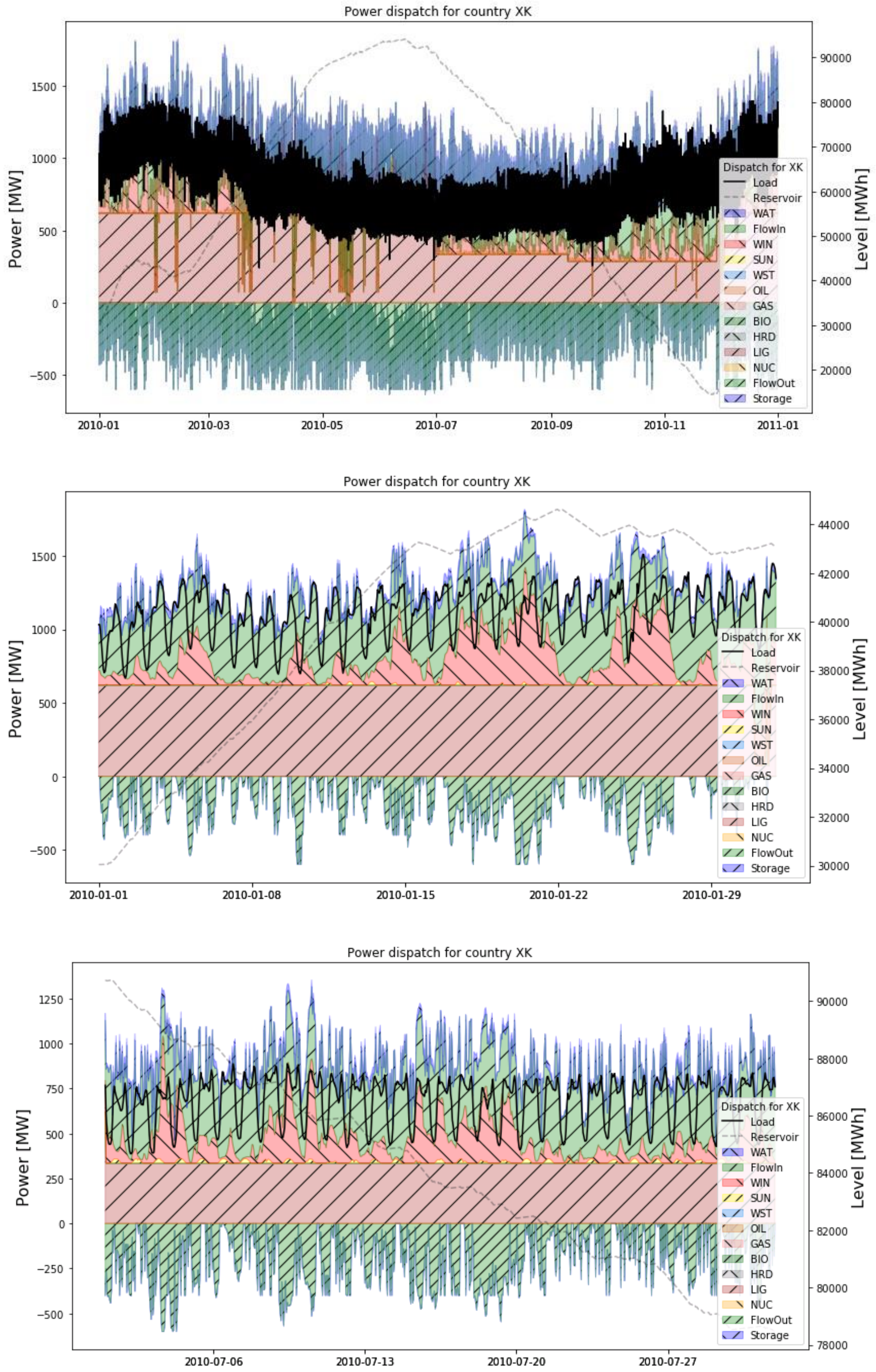

Figure 68 Power dispatch curve in the case C for the year 2020 of Kosovo for whole year (top), January (middle) and July (bottom)

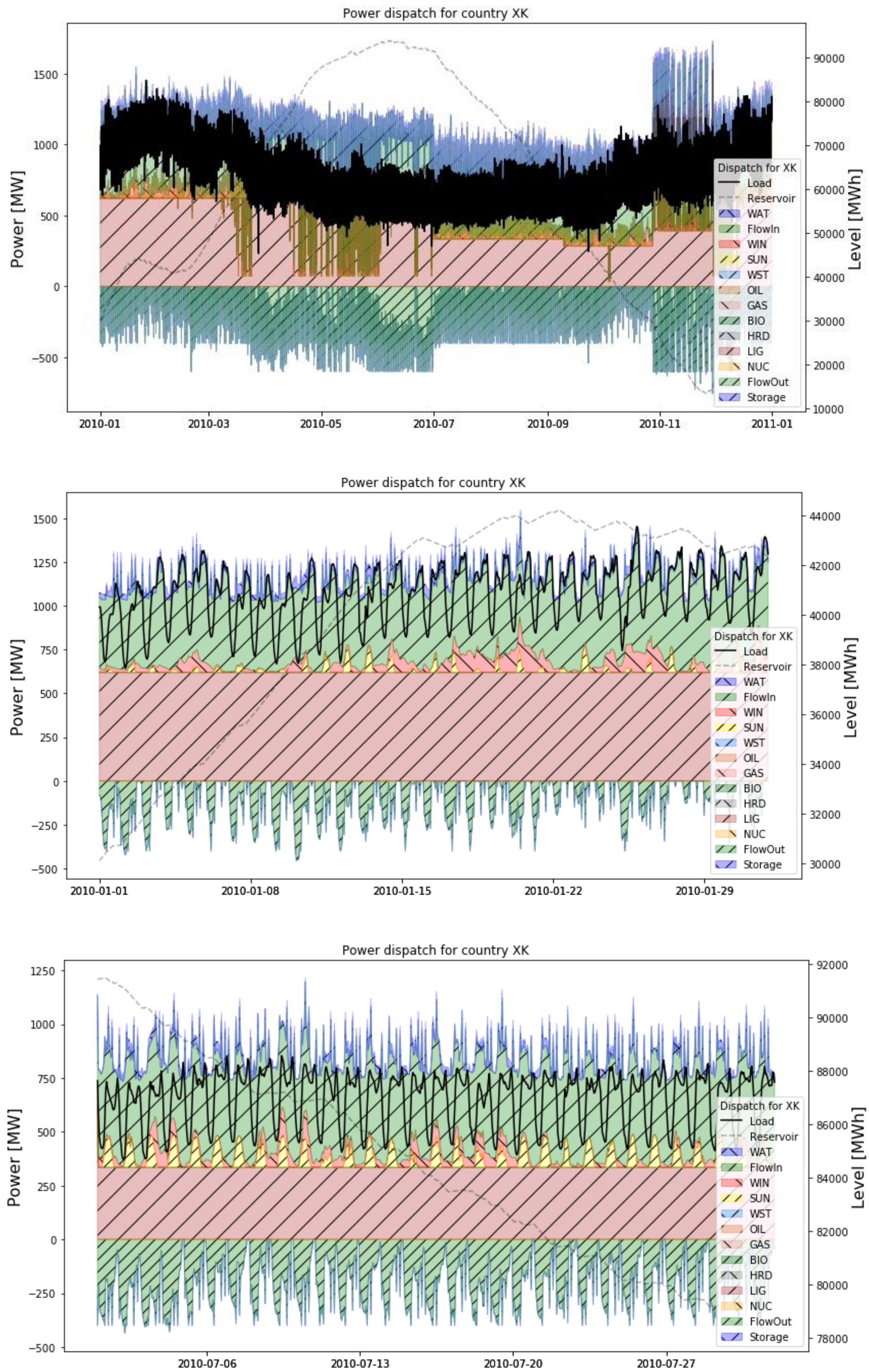

Figure 69 Power dispatch curve in the case B for the year 2030 of Kosovo for whole year (top), January (middle) and July (bottom)

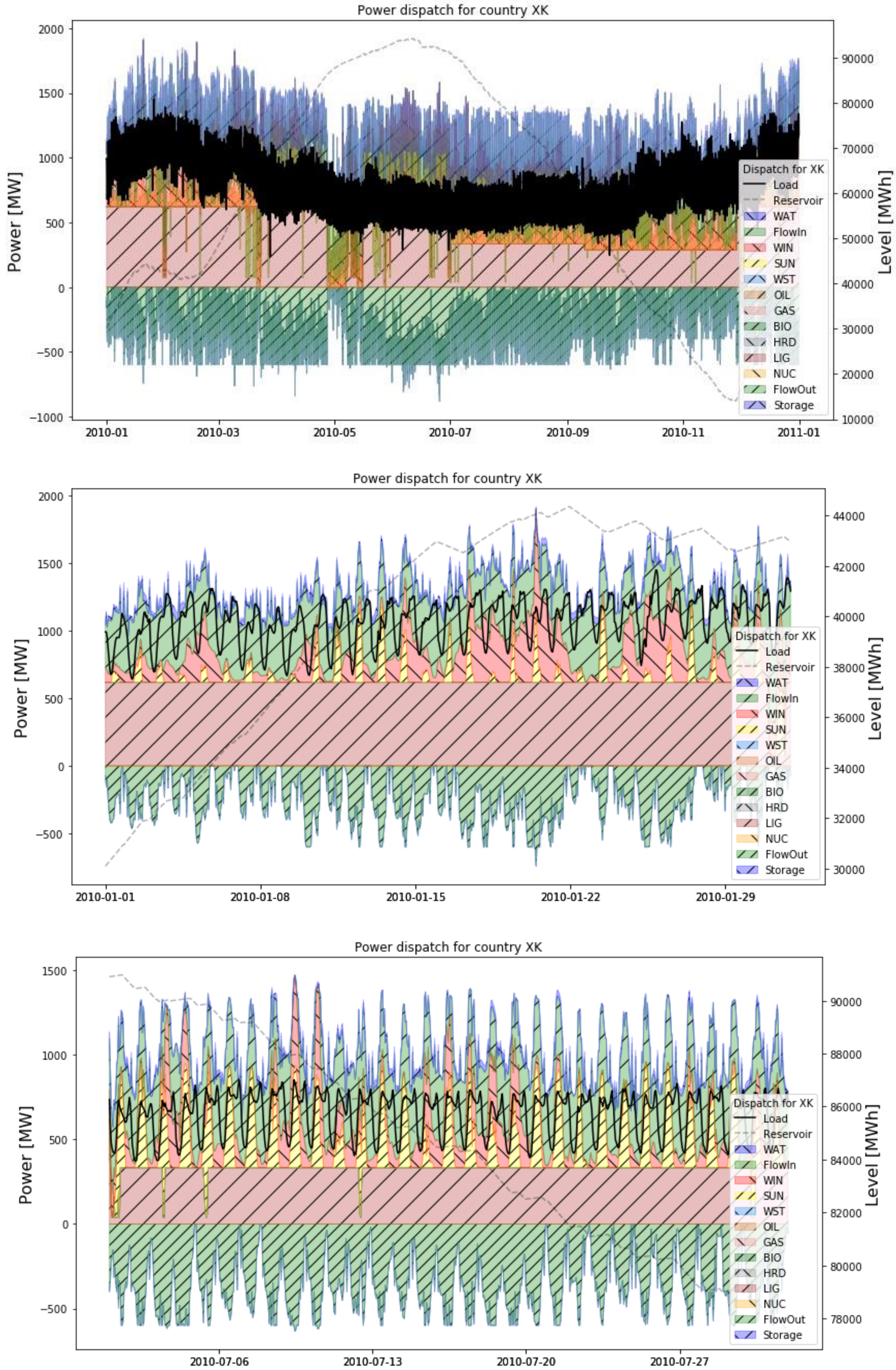

Figure 70 Power dispatch curve in the case C for the year 2030 of Kosovo for whole year (top), January (middle) and July (bottom)

6. CONCLUSION AND FUTURE WORK

This thesis describes implementation of the DispaSET model on the Western Balkans power system. The model has been applied on four Western Balakans Countries: Bosnia and Hercegovina, Kosovo, Montenegro and Serbia. Since each of these four countries has its own power generating units, transmission and distribution networks and final consumers the first task was to gather all the available data relevant for creating a proper model. This included historical fuel prices, power plant data, planned and unplanned outages, river hydrology, weather data, cross border energy flows and accumulation levels of all available storage units. All this data has been statistically and mathematically processed and converted into the formats accessible by the model. The simulation process has been carried out simultaneously for the whole region.

In total there have been three scenarios, a reference one and two alternatives where the latter two include additional three cases describing alternative solutions. Due to the data availability year 2010 has been chosen as the best option for modelling the Reference scenario. The carried out analysis of each of these four power sectors revealed the domination of lignite and hydropower in electricity production, with negligible share of wind and solar in total installed capacities. All the results from simulations have been validated as they accurately represent the data from the real world. The two alternative scenarios have been developed with the purpose of analysing the impact of future strategies and integration of RES on the current power systems. First two cases inside alternative scenarios have been developed according to national strategies for the years 2020 and 2030. For the third case the main goal has been the integration of additional 20% and 30% of RES. Main indicator for validation of the additional scenarios was average price of electricity calculated by the model. It has been shown that integration of RES can indeed lower the price of electricity as 33,65% regarding the input data.

In this thesis it has been proven that all four countries have the potential to operate in the island regime with high share of RES. This is important fact since integration of additional 20% of RES by year 2020 and 34% by the year 2030 would not impact the stability of the existing power system. It would rather increase the regions energy independency as well as its security of supply. Furthermore, high share of RES would have a positive impact on reducing the local air pollution by lowering GHG emissions which would in the end be a positive step towards stalling the process of global warming. The potential problems that could arise through the integration of RES are power curtailment, load shedding and congestions of the transmission lines between neighbouring countries. This issues should be taken into account in the future planning of the power sectors.

The future work should be related to expansion of the current region on neighbouring countries such as Albania, Croatia and FYR of Macedonia with the goal of more accurate description of the energy flows in the region. Moreover, it could be interesting to make a stochastic weather forecasts to see how they will affect future scenarios.

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