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Applying the Dispa-SET Model to the Western Balkans Power System

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ABSTRACT

The ongoing climate change, together with the global increase in energy consumption and unpredictable fossil fuel prices have been the main drivers for the implementation of power exchange, market coupling, energy efficiency measures and larger use of renewable energy. All these targets bring up the need for the development of new modelling frameworks and governance systems that will be based on competitive, secure and sustainable national action plans. For this purpose, the Dispa-SET model has been applied to six countries in the Western Balkans region. In the first scenario, the model has been validated for the year 2010. The second scenario has been developed according to the targets from national energy strategies for the years 2020 and 2030, while the third scenario has been developed with the purpose of determining the maximum share of renewable energy sources in the regional power mix. Simulation results indicate that the integration of additional wind and solar capacities, compared to the short and long-term national strategies for the years 2020 and 2030, can be achieved without compromising the stability of the system.

KEYWORDS

Energy system modelling, Power dispatch, Energy planning, Dispa-SET.

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INTRODUCTION

The six Western Balkan countries, Albania, Bosnia and Herzegovina, Kosovo, Macedonia, Montenegro, and Serbia are not members of the European Union, yet they have started to implement some of the Union's 'acquis communautaire'. For this purpose, an organization was founded by the Treaty establishing the Energy Community which has been signed in October 2005 in Athens, Greece. The objective of the institution is "to extend the EU internal energy market rules and principles to countries in South East Europe, the Black Sea region and beyond on the basis of a legally binding framework" [1]. Thus, European policy goals are becoming increasingly relevant for this complex region, faced with serious energy challenges. Literature suggests that conflicts over the break-up of the former Yugoslavia damaged much of the energy infrastructure and compounded the challenge of providing a stable energy supply [2]. Furthermore, electricity systems in many parts of the region remain fragile and in need of investment as key elements of the energy infrastructure (e.g. major thermal and hydropower plants) were built during the 1960s and 1970s [2].

Background

A survey on climate change adaptation policies and plans in 11 South East European countries [3] has shown that building a climate-ready adaptation society is an urgent issue that cannot be postponed. Statements on security of energy supply for Albania [4], Bosnia and Herzegovina [5], Macedonia [6], Montenegro [7], Serbia [8] and Kosovo [9] suggest that the power supply is mostly dominated by coal (mostly lignite) and hydropower, while other resources such as oil, natural gas, and renewable (mostly wind and solar power) play a minor role. Apart from that, the Western Balkan region is characterized by relatively high levels of energy intensity, up to 2.5 times higher than the average values observed in the EU (European Union) member states [10]. In general, high energy intensity is an indicator of low energy use efficiency and can be attributed to three main factors: degraded state of the energy infrastructure, high energy losses in transformation, transmission and distribution, and inefficiency in the end-use sector [11]. Most states within the Western Balkans region have domestic lignite production which is, like the power plants, owned by the government. A recent study [12] has shown that utilization of Electricity from Renewable Energy Sources) (RES-E) benefits from the synergic operation of the whole system rather than individual technologies. Such systems need to take into account the framework and boundary conditions from the ecological, economic and societal aspects. It is important to note that lack of good governance and some ongoing post-conflict tensions aggravate the societal, economic and environmental impacts of the energy sector. Accessibility and affordability are often prioritized over the promotion of sustainability and intra- and inter-generational equity [13] such as lignite-fired powerplants in Kosovo, and Bosnia and Herzegovina. Exploration of opportunities for RES-E deployment has shown that, although the region is linked with high investment risks, some countries such as Albania and Montenegro are suitable to successfully host RES-E projects in the framework of the EU Directive 2009/28/EC [14]. Regulatory problems, including monitoring, enforcement, and administrative issues need to be resolved in order to create a good business environment for developing RES-E [15]. With appropriate and enforced legislation and good strategic choices regarding which technologies should be given priority, the countries of the Western Balkans could successfully take advantage of the benefits offered by RES-E while complying with their low carbon obligations on their road to the EU [16].

Literature review, summarized in Table 1, highlights a lack of recent studies covering unit commitment and power dispatch optimization on an individual unit level in coal-intensive regions such as Western Balkans. Focus of most studies is dedicated to:

- Long-term planning of individual and in rare cases regional energy systems with limited dispatch analysis;
- Analysis of potential integration of RES-E technologies and their impact on existing grids and/or markets;
- Operation and dispatch of individual units (production, storage, combined heat and power, power to gas) in some highly constrained environments.

In Dominković *et al*. [17], the power system is solved by aggregating generation per fuel type and the study concludes that 100% renewable regional energy system can be achieved if numerous RES-E technologies combined with energy efficiency measures are utilized. In order to achieve such a goal and increase the security of energy supply, no technology should have a higher share than 30% in the regional power mix. In Cebulla *et al*. [18], storage options have been modelled and analysed in REMix, which is a linear, cost-minimizing optimization model determining the installed capacities and dispatch of all power generation and electrical energy storage in a system but does not solve the unit commitment problem. A stochastic Mixed-Integer Linear Programming (MILP) energy planning model with power market dynamics [19] incorporates economic segments and market participation but lacks individual unit dispatch which is modelled as a block bid on a day-ahead market. An outlook for the South-East European power system until 2050 with least-cost decarbonization pathway meeting EU mitigation targets [20] shows that levelised cost of the power supply of that region could potentially end up at 12.1 ctEUR/kWh in 2050. The approach in this research also clusters all units per fuel type rather than considering individual entities.

Some authors have shown that the existing Serbian energy system, with significant hydro generation, available pumped storage hydro capacity, and strong interconnections have the ability to integrate up to 2,500 MW of variable wind generation without compromising the reliability and technical performance of the grid [21]. More recently, they also analysed two different methods for decreasing the flexibility gap in national energy systems [22]. Both studies use Energy PLAN for determining the amount of CEEP in the system and analysing total costs rather than optimizing power dispatch. One of few research articles dedicated to the investigation of an optimal share of renewable sources to be introduced into the power system of Bosnia and Herzegovina [23] has shown that 10% RES-E in the final energy mix would be optimal if external costs were considered. Analysis of hydro potential in Bosnia and Herzegovina [24] has shown that hydropower systems are necessary for a sustainable energy mix. Although this study highlights the importance of having high shares of hydro, a comprehensive system-wide computational analysis was not carried out. Implications of the EU emissions trading system for the South-East Europe regional electricity market were finally analysed in Višković *et al*. [25], taking into account regional interconnectivity and nodal market prices but neglecting operating parameters of individual units.

Adequacy assessments of integrated gas and electrical power systems can be performed by analysing critical situations and the capacity of the system to cover the demands. This kind of analysis is performed in Dokic and Rajakovic [26], demonstrating the importance of sector coupling. The study uses a detailed model of power and gas systems and focuses on one type of power plants without large RES penetration levels. Research on the diversification of wind power [27] also made use of a Unit Commitment and Power Dispatch (UCPD) model, identifying unforeseen benefits and limitations produced by Mean-Variance Portfolio (MVP) optimization. Other studies in this field are mostly techno-economic assessments of cogeneration [28] and/or trigeneration systems [29], or Model Predictive Control (MPC) for demand response [30], in which a price-taker approach is considered.

Because of their policy relevance and contested nature, the transparency and open availability of energy modelling and data are of particular importance [31] and even though individual researchers' choices are important, institutional changes are still also necessary for more openness and transparency in energy research. This paper is also dedicated to filling the gap in the lack of open data, thus the database, containing all the inputs and simulation results are released for public on Github platform (https://github.com/balkans-energy-modelling/Dispa-SET-for-the-Balkans).

To this date, no freely available and open source power system model is available for the Western Balkans regions. This paper describes the adaptation and application of Dispa-SET, a relatively new, open source, entirely editable unit commitment and power dispatch model that focuses on the balancing and flexibility problems in the European grids [32]. It is written in Python and uses .csv and .xlsx files for input data. The optimization is defined either as an LP or MILP problem, depending on the desired level of accuracy and complexity [32]. Its main advantage compared to some of the models described above is the ability to optimize a regional multi-zonal power system with a high level of detail at the individual unit level. It takes into account the minimum and maximum efficiencies, start-up times, minimum up and down times, ramping rates, minimum part loads and CO_2 intensities of conventional power plants, the levels in the accumulation reservoirs and pumped hydropower plants as well as the availability factors of all types of RES-E.

Table 1. Literature overview and comparison

Reference	Category	Tool	Formulation
[17]	(I)	Matlab	LP – system cost
[18]	(I)	REMix	LP – system cost
[19]	(I)	In-house	MILP
[20]	(I)	elesplan-m	LP-MILP hybrid
[21]	(II)	EnergyPlan	Simulation
[22]	(II)	EnergyPlan/GenOPT	Simulation/Optimization
[23]	(II)	EcoSense	Simulation
[24]	(II)	Excel	Simulation
[25]	(II)	In-house	MILP
[26]	(III)	In-house	MILP
[27]	(III)	In-house	MILP
[28]	(III)	In-house	Techno economic assessment
[29]	(III)	Excel/Matlab	Techno economic assessment
[30]	(III)	In-house	MPC

Hypothesis and contributions

One interesting hypothesis resulting from the literature review is that it is possible to phase out a large amount of lignite power plants and replace them by RES-E without compromising the stability and the flexibility of the power system through the expansion of transmission interconnections between the zones and by using a detailed, unit level, bottom-up approach. The goal of this work is to test this hypothesis by using the Dispa-SET model on the six countries from the Western Balkans region. For this purpose, a reference case and two alternative scenarios are developed. The model is first validated for the year 2010. To optimize the development of the system for the 20-year period and to show the robustness of the model and provide more future alternatives, two additional scenarios are then modelled. In Scenario A, implementation of national energy strategies for the years 2020 and 2030 is analyzed. In Scenario B, integration of a high share of renewable energy sources for the same years is analyzed.

METHODS

The aim of the Dispa-SET model [32] is to represent, with a high level of detail, the short-term operation of large-scale power systems, solving the unit commitment problem. Hence, it is considered that the system is managed by a central operator with full information on the technical and economic data of the generation units, the demands in each node, and the transmission network.

The unit commitment problem consists of two parts: scheduling the start-up, operation, and shut down of the available generation units, and allocating (for each period of the simulation horizon of the model) the total power demand among the available generation units in such a way that the overall power system costs are minimized. The first part of the problem, the unit scheduling during several periods of time, requires the use of binary variables in order to represent the start-up and shut down decisions, as well as the consideration of constraints linking the commitment status of the units in different periods. The second part of the problem is the economic dispatch problem, which determines the continuous output of each and every generation unit in the system.

The problem mentioned above can be formulated as a MILP. The formulation is based on publicly available modelling approaches [33-35]. The goal of the model being the simulation of a large interconnected power system, a tight and compact formulation has been implemented, in order to simultaneously reduce the region where the solver searches for the solution and increase the speed at which the solver carries out that search. Tightness refers to the distance between the relaxed and integer solutions of the MILP and therefore defines the search space to be explored by the solver, while compactness is related to the amount of data to be processed by the solver and thus determines the speed at which the solver searches for the optimum.

Objective function

The goal of the unit commitment problem is to minimize the total power system costs [expressed in EUR in eq. (1)], which are defined as the sum of different cost items, namely: start-up and shut-down, fixed, variable, ramping, transmission-related and load shedding (voluntary and involuntary) costs. The demand is assumed to be inelastic to the price signal. The MILP objective function is, therefore, the total generation cost over the optimization period:

$$\text{Min}\, SystemCost = \sum_{\forall u,i} \left(\begin{array}{c} CostStartUp_{i,u} + CostShutDown_{i,u} + \\ CostFixed_{u} \times Committed_{i,u} + \\ CostVariable_{i,u} \times Power_{i,u} + \\ CostRampUp_{i,u} + CostRampDown_{i,u} + \\ PriceTransmission_{i,l} \times Flow_{i,l} + \\ \sum_{n} \left(CostLoadShedding_{i,n} \times ShedLoad_{i,n} \right) + \end{array} \right) \tag{1}$$

Since the simulation is performed for a whole year with a time step of one hour, the problem dimensions are not computationally tractable if the whole time-horizon is optimized. Therefore, the problem is split into smaller optimization problems that are run recursively throughout the year. Figure 1 shows an example of such an approach, in which the optimization horizon is one day, with a look-ahead (or overlap) period of one day. The initial values of the optimization for day *j* are the final values of the optimization of the previous day. The look-ahead period is modelled to avoid issues linked to the end of the optimization period such as emptying the hydro reservoirs or starting low cost but non-flexible power plants. In this case, the optimization is performed over the horizon of 48 hours, but only the first 24 hours are conserved.

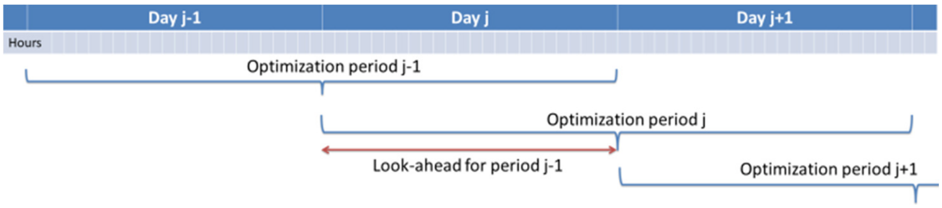


Figure 1. Time horizons of the optimization with the look-ahead period

Constraints

A detailed formulation of the Dispa-SET model is out of the scope of this paper. A detailed description of all equations and constraints is available in Quoilin *et al.* [32]. The summary of the main model features are:

- Minimum and maximum power outputs;
- Power plant ramping limits;
- Reserves up and down;
- Minimum up/down times;
- Load shedding;
- Curtailment;
- Pumped-hydro, battery and thermal storage;
- Non-dispatchable units (e.g. wind turbines, run-of-river, etc.);
- Start-up, ramping and no-load costs;
- Multi-nodes with capacity constraints on the lines (congestion);
- Constraints on the targets for renewables and/or CO_2 emissions;
- Combined Heat and Power (CHP) min/max power and heat outputs;
- Yearly schedules for the outages (forced and planned) of each unit.

Inputs and parameters

The main model inputs are the load curve and the Variable Renewable Energy (VRE) generation curves. The model can operate under two different approaches: integrating the VRE into a residual load curve or considering VRE as power plants with must-run constraints.

Since this model focuses on the available technical flexibility and not on accurate market modelling, it is run using the measured historical data, and not the day-ahead forecasted load and VRE production. This can be partly justified by the fact that a fraction of the forecast errors can be solved on the intra-day market. This perfect foresight hypothesis is however optimistic, and a more detailed stochastic simulation should be performed to refine the results.

Powerplant data includes min/max capacity, ramping rates, min up/down times, start-up times, efficiency, variable cost (fuel prices are historical fuel prices for the considered period). It is worthwhile to note that some of the units, such as gas turbines, present a low capacity and/or high flexibility whose output power does not exceed a few MW, and which can reach full power in less than 15 minutes. For these units, a unit commitment model with a time step of 1 hour is unnecessary and computationally inefficient. Therefore, these units are clustered into one single, highly flexible unit with averaged characteristics.

SCENARIOS

A reference case and two alternative scenarios, each including two alternative 2020 and 2030 cases have been developed. In addition, the model has been validated against the year 2010, which has been chosen due to data availability. Each of the alternative scenarios has two cases. Cases A and C are developed according to the national energy strategies of each country for the years 2020 and 2030, respectively. Likewise, cases B and D are strategies with a high penetration of RES-E in the regional power sector for the years 2020 and 2030, respectively. The main purpose of cases A and C is the validation of the individual strategies proposed by national Transmission System Operators (TSO) and government's annual energy reports with a view to their impact on the region's combined power system. The goal of scenarios B and D is to understand how higher RES-E penetration levels would affect the regional power system. Figure 2 is a graphical representation of the region. Installed capacities and cross border interconnections are scaled to size for comparison reasons. Black lines represent upgraded interconnection capacities used in the 2030 scenario.

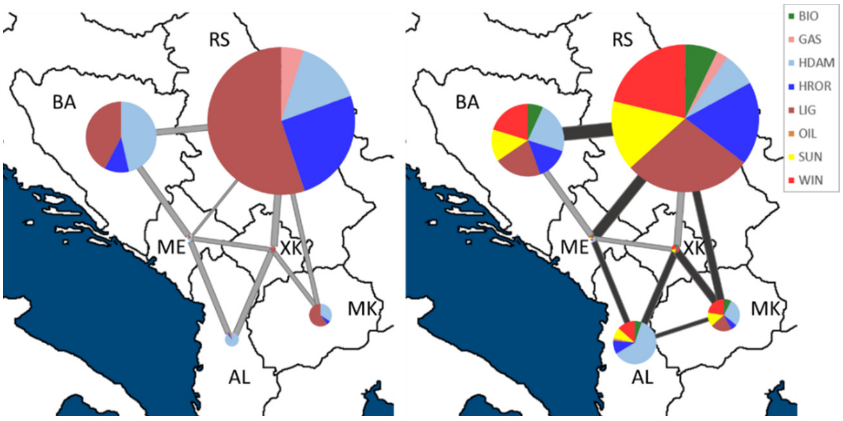
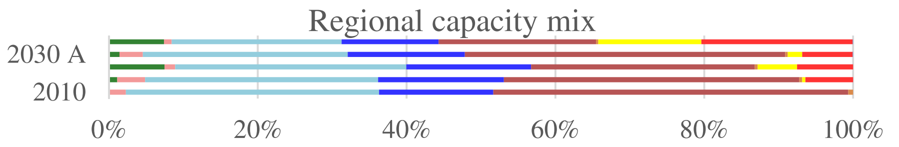


Figure 2. Map of the region with installed capacities and cross border interconnections in 2010 (left) and 2030 (right)

Previous studies have already proven that Bosnia and Herzegovina and Serbia have a significant potential for renewable resources mostly in terms of additional small hydro (< 10 MW), wind, solar and biomass [15]. This is especially the case for Serbia's biofuel production from waste and biomass [36]. If by the year 2050 the whole RES-E potential is utilized, the maximum share of renewables in the Macedonian energy mix could sum up to around 50% if no energy efficiency measures are applied [37, 38]. Among the six analyzedcountries, Montenegro has the highest wind potential, mainly due to the mountain ranges along the coastline [39]. The country with the lowest estimated generation from RES-E (around 10% in the year 2025), is Kosovo, mostly due to the unfavourable climate conditions [40]. According to these studies' integration of RES-E in the region has been estimated to 11.7% for the year 2020 and 28.7% for 2030. Since forecasting of the future 2020, 2030 and 2050 electricity demands have already been researched within the South East Europe 2050 Carbon Calculator project, this part is out of the scope of this paper [41]. A summary of regional capacity mixes from all five cases is presented in Figure 3. This scenario analysis helps to understand how Greenhouse Gas (GHG) emissions could be reduced, energy imports from the surrounding countries optimized and how the stability of the region's power system and its security of supply could be improved.



	2010	2020 A	2020 B	2030 A	2030 B
■ BIO	0	278	1850	413	2600
■ GAS	353	917	353	917	353
■ HDAM	5294	7654	7654	8009	8009
■ HROR	2386	4140	4140	4578	4578
■ LIG	7419	9719	7419	12519	7419
■ OIL	98	98	98	98	98
■ SUN	0	103	1306	570	4854
■ WIN	0	1565	1852	1974	7141
■ WST	0	0	0	10	10

Figure 3. Regional capacity mix in all scenarios

Fuel prices

Table 2 summarizes fossil fuel prices in the Western Balkans. Although it is difficult to determine the real price of lignite (most countries have a complex and relatively non-transparent subsidy system), Kovacevic [42] estimates that it could be in the range of 7 to 11 EUR/MWh. These prices have been adopted for all six countries in this study. Historical natural gas prices from 2010 have been averaged to 25 EUR/MWh [43]. Since the whole region has an abundance of biomass, its price in 2010 was relatively low when compared to other European regions. It is estimated that, on average, biomass chips could be bought for 10 to 13 EUR/MWh [44], depending on the region. Fuel prices in future scenarios have been adjusted for an annual inflation rate of 2%.

Table 2. Estimated fuel prices in the Western Balkans region (prices in brackets are actual prices from 2010)

Fuel type	Price [EUR/MWh]			Ref.
	2010	2020	2030	
Biomass	12 (10-13)	14.63	17.83	[4-7] [8, 9, 42-44]
Lignite	8 (7-11)	9.75	11.89	
Natural gas	25 (20-35)	30.47	37.15	

Electricity demand

Figure 4 presents the electricity demand of all six countries from the Western Balkans region. Serbia leading with the peaking demand of 6,601 MW and total annual electricity consumption of 34,445 GWh [8] is closely followed by Bosnia and Herzegovina (2,173 MW/12,075 GWh) [5], Macedonia (1,626 MW/8,016 GWh) [6], Albania (1,601 MW/6,773 GWh) [4], Kosovo (1,155 MW/5,711 GWh) [9] and Montenegro (813 MW/3,926 GWh) [7]. The combined peak load (10,741 MW) during the winter is almost twice as high as the one in summer (6,432 MW), mainly due to the fact that, besides increased lighting needs, additional 20-35% of the population consumes electricity for space heating [4-9]. Electricity demand used for the preparation of domestic hot water in the whole region remains relatively constant throughout the year and is equal to 1-3% of the total electricity demand.

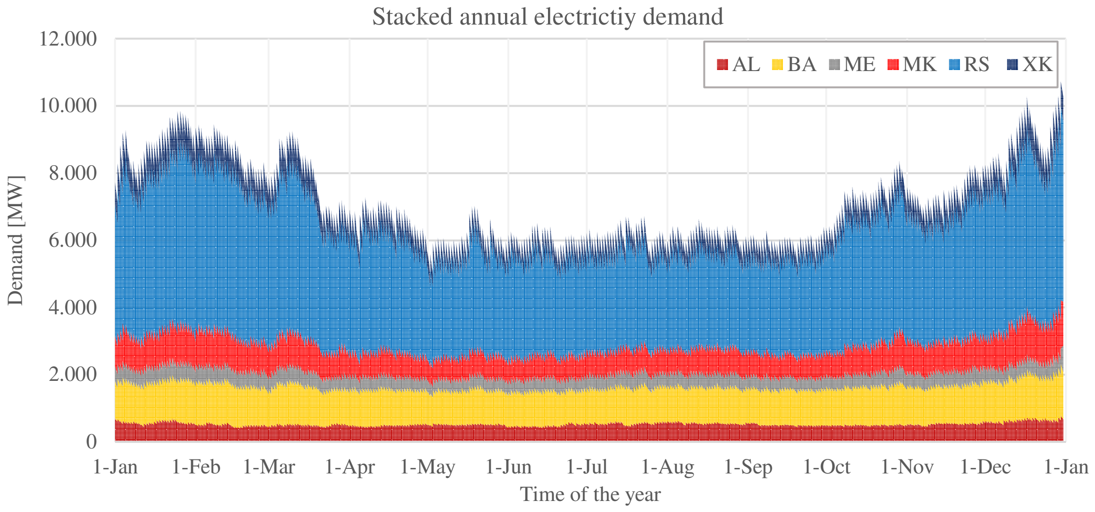


Figure 4. Stacked annual hourly electricity demand from all six countries in the region

Electricity production

In the year 2010, 103 hydropower plants and 19 thermal power plants generated electricity in the Western Balkans region. Hydropower plants are divided into a Hydro

Run-of-River (HROR), Hydro Dam (HDAM) and Pumped Hydro Storage (HPHS) units. Thermal power plants are divided into lignite- and oil-fired Steam Turbine Power Plants (STUR) and natural gas-fired Combined Cycle Power Plants (COMC).

Table 5, provided in Annex A of this paper, is a list of all HDAM units in the region. Technical parameters such as nominal installed capacities, flow rates, nominal head, volume and storage capacities of accumulation reservoirs are also included. The total installed capacity of all HDAM units in the region sums up to 5,288 MW. Of that 26.45% is located in Albania, 33.13% in Bosnia and Herzegovina, 12.73% in Montenegro, 8.88% in Macedonia, 18.13% in Serbia and 0.66% in Kosovo. The largest HDAM in the region is HE Koman located in Albania, with a nominal capacity of 600 MW. In terms of accumulation capacity, the largest HDAM is HE Bistrica (potential energy of 7,834,593 MWh), located in Serbia and HE Fierza (accumulation volume of 2,300,000 m^3), located in Albania. The accumulation period in these units ranges from three to five days in the case of HE Koman and HE Salakovac and up to several months for HE Trebinje 1 and HE Bistrica. Among all those 31 units, two are pumped-hydropowerplants (HPHS), RHE Čapljina with turbine power capacity of 420 MW and a pump power capacity of 250 MW, located in Bosnia and Herzegovina, and RHE Bajina Bašta with a turbine power capacity of 614 MW and pump power capacity of 616 MW, located in Serbia.

Table 6, provided in Annex A of this paper, is a list of all the HROR units in the region. Technical parameters such as nominal installed capacities and flow rates are also included. The total installed capacity of all the HROR units in the region sums up to 2,316 MW. Out of this total, more than half (around 57.34%), comes from the Djerdap 1 and Djerdap 2 units, located on the Serbo-Romanian border, while the remaining capacity is spread over 70 smaller ones, with an average of 14 MW. All these HROR units are mainly used as baseload units whose production is proportional to the discharge rates of the rivers on which they are situated.

Table 7, provided in Annex A of this paper, is a list of all thermal units in the region. Technical parameters such as minimal and maximal efficiencies, start-up times, minimum up and down times, ramping rates, minimal part loads and CO_2 intensities are also included. The total combined installed capacity of all STUR and COMC units sums up to 7,870 MW. Of that, the two Serbian power plants Nikola Tesla A and Nikola Tesla B amount to more than 33.82% of the total installed capacity in the region. The smallest power plant has an installed capacity of 45 MW and is located in Sremska Mitrovica, Serbia. The only oil-fired power plant in the region is TE Vlora, located in Albania, but according to [4], it can only operate at the reduced capacity of 35 MW and is mainly used for providing reserve services or peak covering during unfavorable weather conditions. The only three natural gas-fired COMC units are located in Serbia. They were initially built as peaking power plants, but due to the ongoing drop in the price of electricity in neighbouring countries their annual operation is limited only to a couple of hours in a year. All the technical data related to the operating parameters of the power plants is discussed in more detail in other scientific publications [45, 46].

Outage factors

Outage factors represent either the time intervals in which regular maintenance is scheduled or time intervals when each unit is unavailable due to expected and unexpected malfunctions. During these periods, power plants are limited to partial or no production at all. Depending on the power plant design, this number can be relatively high if there is only one generator, block or turbine available, or relatively small if there is a single unit comprising multiple smaller ones. Data on historical planned outages are usually available in annual TSO reports and can be used to predict future trends since regular maintenance operations are scheduled in similar periods during the year. Outage factors from the largest thermal units in 2010 are presented in Figure 5. For the sake of clarity, all outage factors for each zone are clustered into one line, but they are provided on a unit basis in the model. An outage value of 1 corresponds to a complete outage, while 0 represents full availability. Planned outages are usually scheduled in a way to avoid having two power plants off the grid at the same time inside each zone in order to have enough reserve capacity at disposal for balancing out the system. Thermal power plants TE Vlora, TE Tuzla and TE Pljevlja have only one generation block, which means that they are not able to operate at reduced capacity and thus can have outage factor of either 0 or 1. Other STUR units from the region have variable outage factors as only one or two generation blocks are scheduled for maintenance.

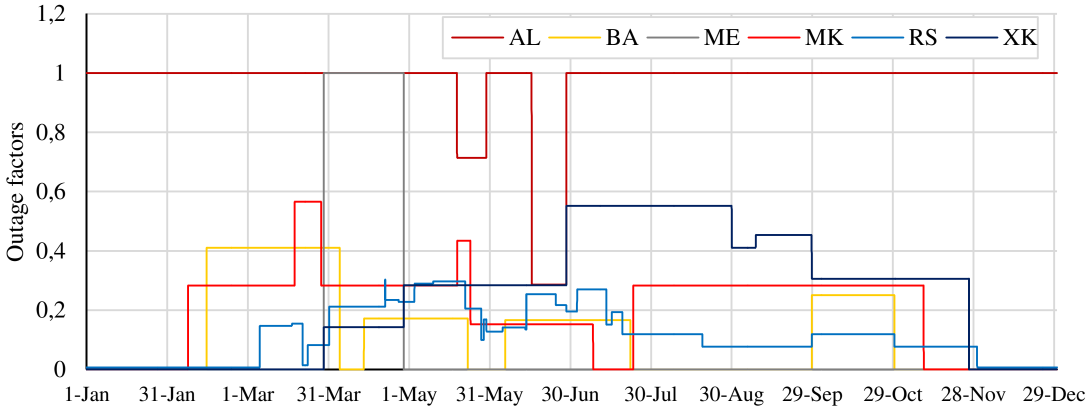


Figure 5. Aggregated outage factors in the region

Renewable energy sources

In the model, the power outputs of solar Photovoltaics (PV), wind energy and hydropower are defined through the Availability Factors (AF). These hourly time series represent the fraction of the nominal power capacity that an RES-E powered power plant can produce at each hour. Examples of AF for wind and solar power plants in the region are presented in Figure 12 and Figure 13 and provided in Annex B of this paper, respectively. It appears clear that the whole region experiences higher wind speeds, and thus higher AF, and lower PV output during the winter and lower wind speeds and higher PV output during the summer. Hourly values of power outputs for solar power plants are obtained from various open source databases [47] and scaled using values of global irradiation from the PVGIS tool [48]. Such AF's are used in both alternative scenarios.

Hydro data is divided between HROR, HPHS and HDAM power plants. The power output of HROR units is determined only by the availability factors, while the power output of HDAM and HPHS power plants depends on the accumulation levels, inflows into the reservoir and the optimization of economic dispatch. River inflows are given as an hourly time series that has been normalized to values in the range between 0 and 1. For river discharge rates lower than the installed nominal turbine flow, availability factors are in the range from 0 to 1. For higher river discharge rates, availability factor is set to the maximum value. Scaled inflows are derived from exogenous sources to the level (or state of charge) of the reservoir and are expressed in MWh/h [32]. The river discharge rates and the availability factors of the largest HROR units from the region are presented in Figure 6.

Figure 7 shows the levels of some of the large HDAM units together with the normalized inflow time series (scaled inflows). These two diagrams show that in time intervals with scaled inflows higher than 1, the amount of energy stored in the accumulations is rising and vice versa, when scaled inflows are lower than 1 and HDAM units are required to operate at the full capacity and the amount of energy stored in the accumulations is decreasing.

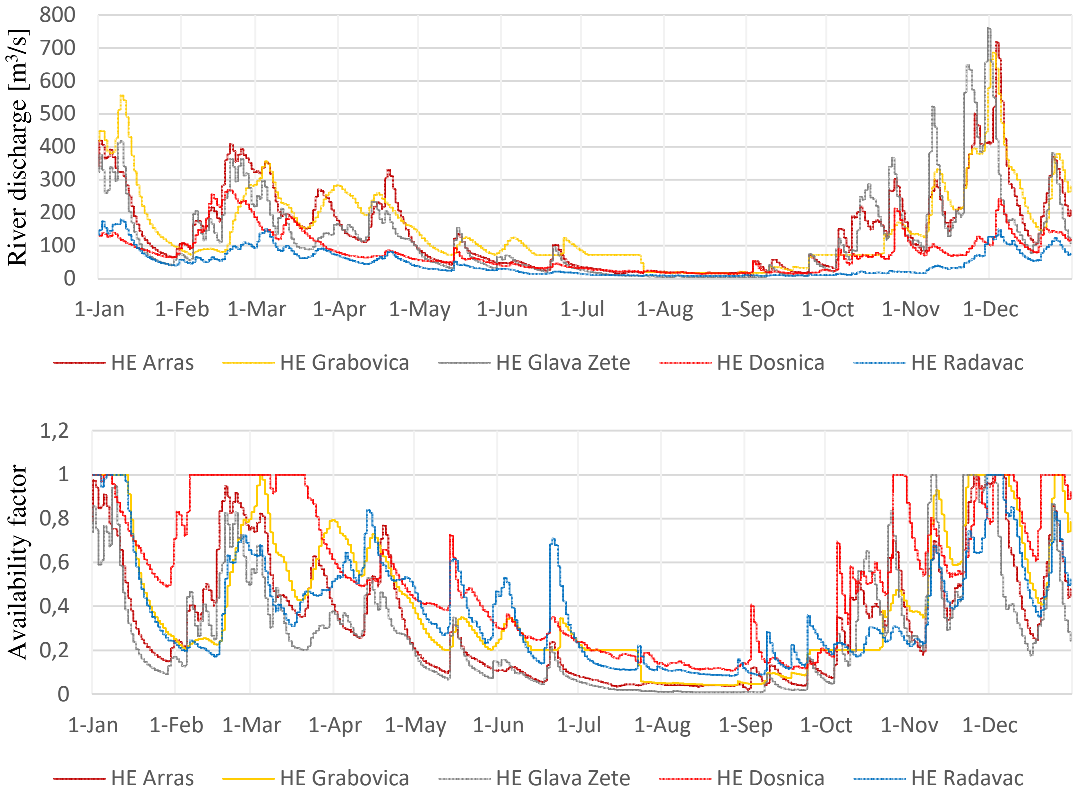


Figure 6. Hourly AF of five HROR power plants from the region

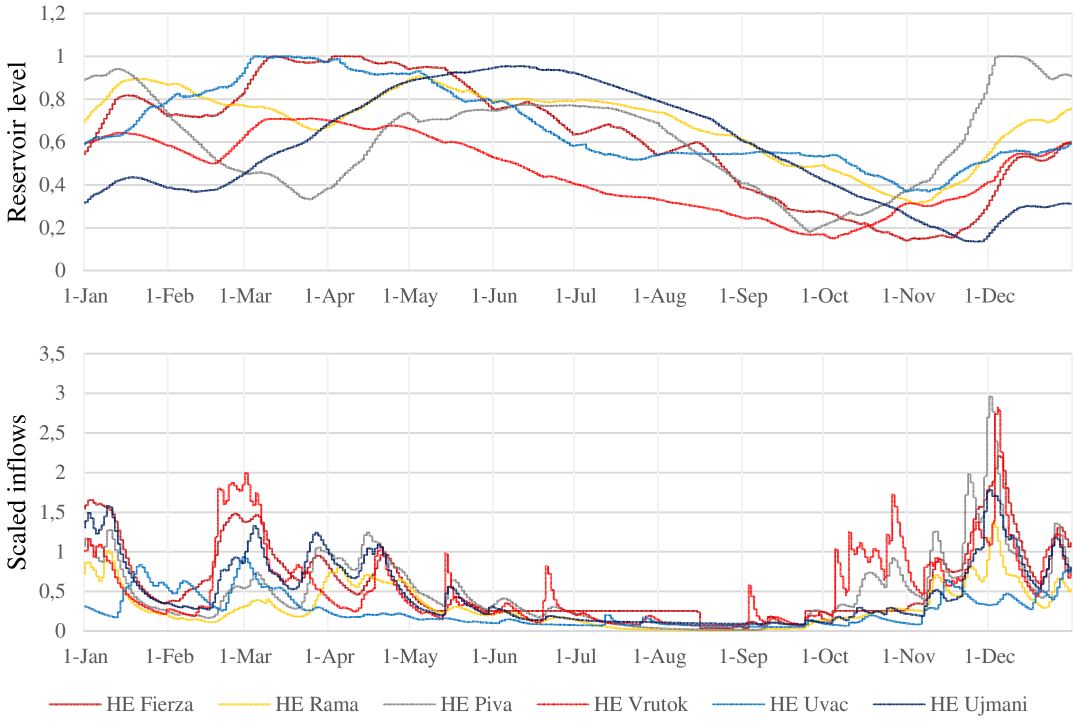


Figure 7. Reservoir levels and scaled inflows from 6 of the largest HDAM in the region

Net transfer capacities

Figure 8 shows the Net Transfer Capacities (NTC) used in the scenarios. They represent the capacities in the interconnection lines between two neighbouring countries that are available for trading on day-ahead markets. They are provided as hourly time series and are expressed in MW [49]. The values have been obtained from different sources such as the KOSTT's list of new transmission capacities and interconnection lines [50] and ENTSO-E NTC transmission system map [51], or, when not available, calculated according to the voltage levels in the transmission lines [52].

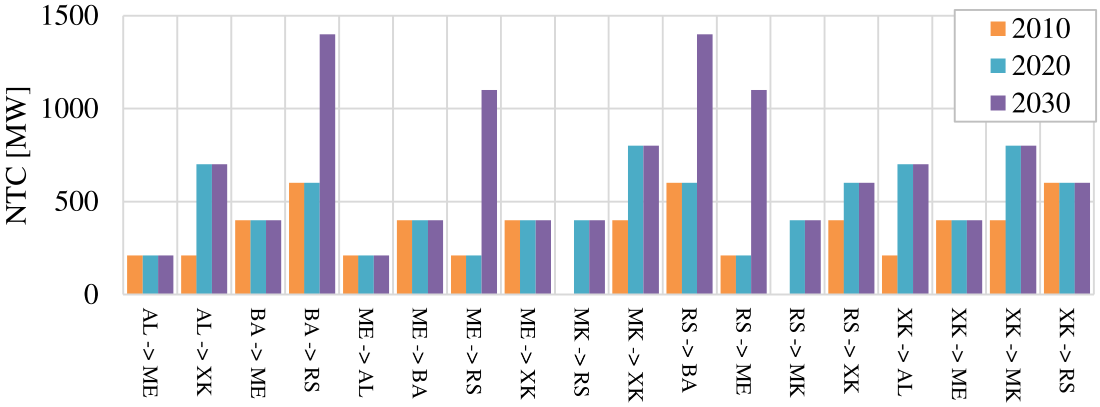


Figure 8. NTC capacities between all countries from the Western Balkans region

RESULTS AND DISCUSSION

The section presents results from the three analysed scenarios. I important indicators from the simulations include the average cost of electricity (during the period of one year), the amount of curtailed RES-E, load shedding due to the lack of available capacities, the amount of congestion in the transmission lines and the power output of each unit or cluster of units. In order to validate the accuracy of the model, simulated results from the reference scenario have been compared to the historical data obtained from various sources such as national reports [4-9], the ENTSO-E Transparency platform [53] or other power sector related publications. The accuracy of the model is presented in Table 3, showing that most values are within 10%. The only significant difference between the simulated and real-life values is the power output of inflexible thermal units in Kosovo and Montenegro. The main reason behind this, is that Dispa-SET determines the optimal flows between all simulated zones while in real life, electricity production depends on additional factors such as bilateral power exchange agreements, political influence, network condition, local dispatch decisions, etc.

Table 4 shows the statistical data of the whole region. As expected, the average cost of electricity is lower in all alternative scenarios than in Reference one. The main reason for such a decrease is the additional amount of renewable energy with no marginal costs. In both future scenarios, the total electricity consumption and peak loads are higher than in the Reference one. These values originate from external projections of future trends, as mentioned earlier. No power exchange with the neighbouring countries of the six Western Balkans countries is allowed in these scenarios. This implies that the region is self-sufficient and does not import electricity from e.g., Bulgaria, Croatia, Greece, Hungary or Romania. In order to make this transition possible, transmission capacities between the six Western Balkans countries have been significantly increased as shown in Figure 8. According to the national strategy, Kosovo is planning to install a new high capacity lignite-fired STUR unit which would lead to a total switch from being the country that imports most electricity to a country that exports the highest amount of electricity in the region. The opposite would happen to Bosnia and Herzegovina, currently one of the major exporters in the region. That is expected to drastically decrease in future scenarios, so Bosnia and Herzegovina could even potentially become import dependent.

Table 3. Comparison of the results from Dispa-SET and the historic real-life values from the national reports

Zone	National reports [GWh]	Dispa-SET [GWh]	Difference [%]	Ref.
TPP units				
Albania	28	0	100.00	[4]
Bosnia and Herzegovina	7,683	7,575	−1.41	[5]
Montenegro	1,272	1,673	31.60	[7]
Macedonia	4,277	3,993	−6.64	[6]
Serbia	23,384	24,271	3.79	[8][54]
Kosovo	4,876	3,077	−36.90	[9]
HDAM units				
Albania	6,490	6,816	5.03	[4]
Bosnia and Herzegovina	6,578	6,117	−7.00	[5][55]
Montenegro	2,729	2,966	8.67	[7]
Macedonia	2,048	2,066	0.90	[6]
Serbia	2,158	2,043	−5.34	[8][54]
Kosovo	119	120	0.61	[9]
HROR units				
Albania	329	321	−2.42	[4]
Bosnia and Herzegovina	1,471	1,471	2.51	[5][55]
Montenegro	21	21	0.01	[7]
Macedonia	346	346	−2.19	[6]
Serbia	10,293	10,310	0.17	[8][54]
Kosovo	37	37	0.10	[9]
Total production				
Albania	6,847	7,137	4.23	[4]
Bosnia and Herzegovina	15,695	15,163	−3.39	[5][55]
Montenegro	4,022	4,660	15.88	[7]
Macedonia	6,679	6,406	−4.10	[6]
Serbia	35,835	36,624	2.20	[8][54]
Kosovo	5,032	3,234	−35.74	[9]

Table 4. Statistical results from the analysed scenarios

	Name	Units	2010	2020		2030	
			Ref.	Case A	Case B	Case C	Case D
	Average electricity price	[EUR/MWh]	17.343	16.312	15.443	15.270	9.279
	Total consumption	[TWh]	70.944	83.657		85.527	
	Peak load	[MW]	13,577	16,058		16,454	
Net imports	Albania	[TWh]	−0.365	3.466	3.023	4.064	1.371
	Bosnia and Herzegovina	[TWh]	−3.603	−0.537	−4.489	1.875	0.628
	Montenegro	[TWh]	−0.734	−4.185	−1.873	−3.007	−1.559
	Macedonia	[TWh]	1.610	3.880	2.711	4.198	2.253
	Serbia	[TWh]	−2.181	−1.836	−6.550	2.651	−6.789
	Kosovo	[TWh]	2.478	−0.788	3.178	−9.782	4.096

Cross-border flows

The cross-border flows between all six countries are presented in Figure 9. In the reference scenario, the whole region has net exportation to the surrounding countries. The main reason for this is favourable weather conditions with relatively high precipitation which caused record production from HROR and HDAM units. In the observed region, the highest total imports are observed in Kosovo and Serbia while the highest exports are in Serbia and Bosnia and Herzegovina. Results from other scenarios indicate that the integration of higher shares of RES-E, combined with the upgrading of the cross-border infrastructure between some countries from the region would have a significant impact on the region's electricity flows. According to national strategies, for the years 2020 and 2030, in cases A and C, Kosovo could become the region's main electricity exporter. This would be a consequence of the plan described above to significantly increase the current lignite production capacities. Results for these two cases show that electricity flows would change from the current north to south direction, where Bosnia and Herzegovina and Serbia cover the lack of local production in Macedonia and Kosovo, to a more centralized pattern, in which Kosovo balances out the lack of local production in Albania, Macedonia and Serbia. In both cases of the high RES-E scenario, the energy flows between the zones are decentralized. In many time intervals, surplus electricity, for example from Macedonia, is transferred all the way to Albania, Serbia, and Bosnia and Herzegovina and vice versa. Thus, a higher share of RES-E in the region's power mix would encourage more electricity flows between the countries and would also lower the average price of electricity.

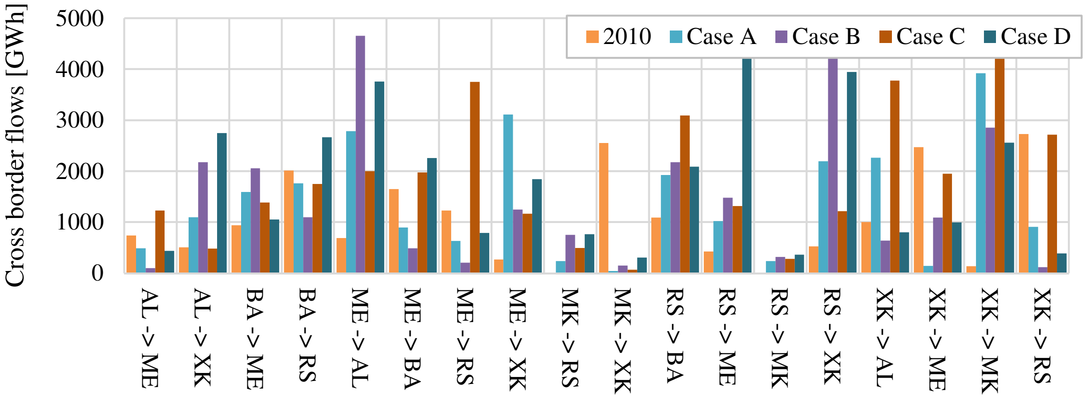


Figure 9. Cross-border flows between neighbouring zones in all 5 cases

Energy mix

The fuel mixes in each zone and for all three cases are presented in Figure 10. It appears that, in the Reference scenario, the entire region is dominated by only two fuel types, lignite and hydropower. Albania is the only country that runs 100% on hydropower. At the same time, Kosovo has the highest share of lignite which is expected to increase slightly from 44.57% to 44.94% in the year 2020. In the year 2030, the share of hydropower in the regional energy mix is expected to drop down to 46.51%. The main reason for this, is the higher local demand growth in comparison to the installation of new hydro capacities. According to national strategies, regional electricity production from lignite is expected to drop from 55.43% in the Reference scenario down to 50.97% by the year 2020 and 47.76% by the year 2030. In alternative high RES-E scenarios, electricity production from lignite is expected to drop even more, down to 43.39% by the year 2020 and 24.76% by the year 2030. The main reason for such a significant drop is the installation of new wind and solar capacities followed by biomass-fired STUR units which can also be used for balancing the system.

According to national strategies, the local solar energy production is expected to increase up to 0.18% by the year 2020 and 0.90% by the year 2030. These targets are quite conservative. The results from the alternative high RES scenarios have shown that integration of 2.07% by the year 2020 and 7.49%, by the year 2030 is possible without compromising the system. The whole region has favourable wind conditions with average wind speeds ranging from 6-9 m/s and average capacity factors around 23-27%. According to national strategies, there are plans to install around 3.86% of wind energy by the year 2020 and up of 4.75% by the year 2030. In the high RES-E scenarios, the share of wind energy in the region's electricity production reaches 4.84% by the year 2020 and 17.45% by the year 2030. According to national strategies only 0.04% of biomass should be utilized by the year 2020 and 0.06% by the year 2020. Since the whole Western Balkans region has higher than EU average biomass potential, a more significant utilization is considered in the high RES-E scenarios. The total share of biomass reaches 3.78% and 4.79% by the years 2020 and 2030, respectively. In consequence, the electricity system would be more diverse, independent of fuel imports, and potentially offer lower wholesale prices.

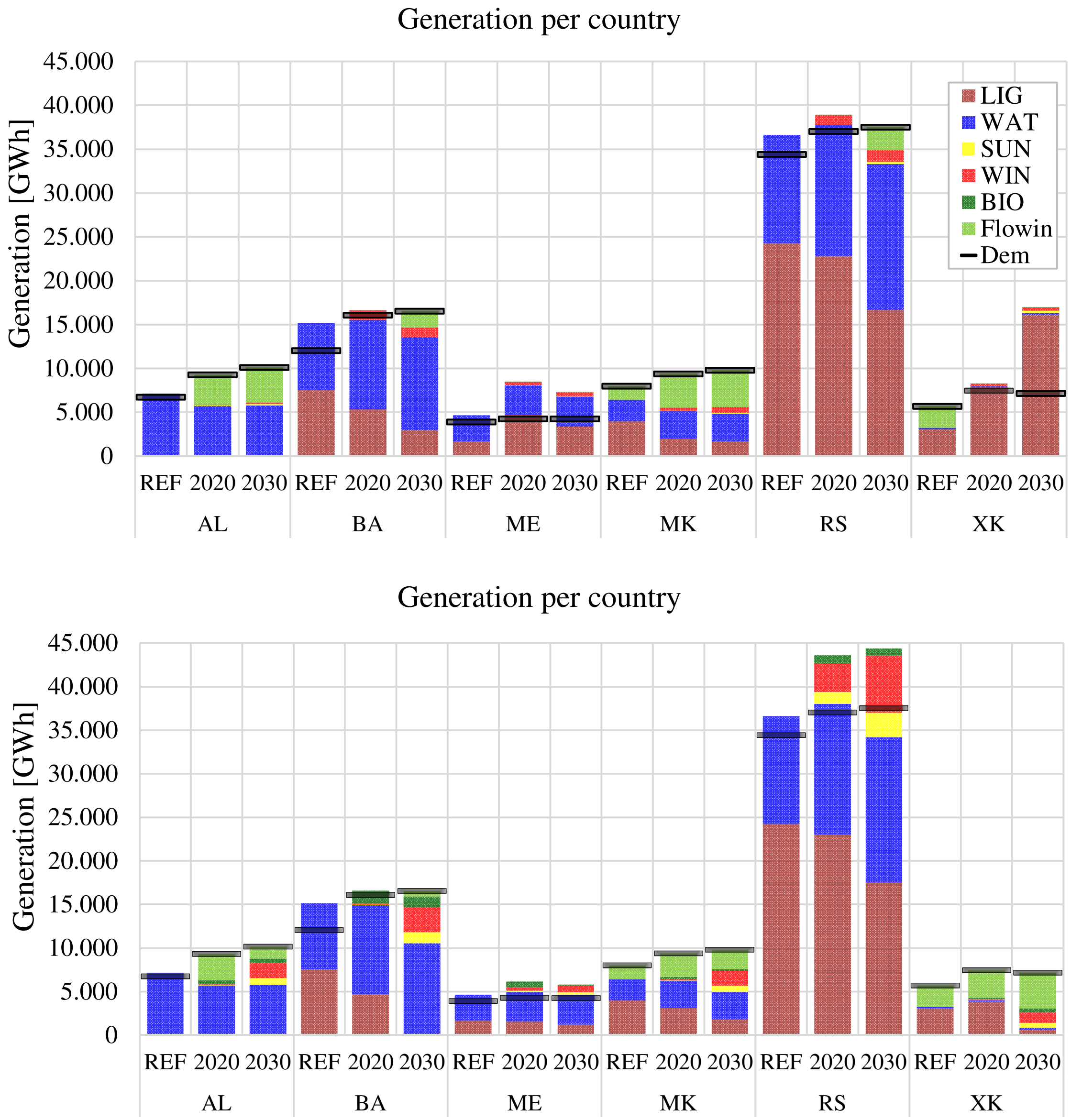


Figure 10. Fuel mixes from the national 2020 and 2030 strategies (top) and high RES-E 2020 and 2030 alternatives (bottom) compared to the Reference scenario (the horizontal lines indicate the annual demand)

Power dispatch and balancing

Another part of this research was dedicated to the stability of the regional and national power systems. In order to visualize how different fuel mixes impact the balancing power dispatch curves for the Reference and high RES-E 2030 cases for Bosnia and Herzegovina are presented in Figure 11. More detailed weekly representation can be found in Figure 14 to Figure 18, provided in Annex C of this paper. In the Reference scenario, the domestic demand in Bosnia and Herzegovina is covered through base-load power plants such as lignite-fired STUR and HROR units and peaking power plants such as HDAM units and imports from the neighbouring countries. This is the traditional merit order of powerplants before the deployment of renewable energy. In the Reference scenario, domestic lignite-fired STURs cover most of the base load while the hydropower from HDAM units is used for covering peak loads or exports to the neighbouring countries. The highest exports can be observed during the winter and spring months when river hydrology and weather conditions are favourable for hydro production. The lowest exports happen during the summer and autumn months when regular maintenance and major overhauls are scheduled. In such systems, balancing is not an issue, except if large STUR units are offline, in which case load shedding and RES-E curtailment could occur. On the other hand, when the whole system is 100% RES-E powered, the risk of load shedding and RES-E curtailment is much higher. The diagrams from the high RES 2030 scenario clearly show that Bosnia and Herzegovina could be entirely powered by RES sources, but only if the available NTC capacities between neighbouring countries are high enough to be used for balancing purposes. In the alternative high RES 2030 scenario, most of the local demand from Bosnia and Herzegovina is covered by renewables such as solar and wind power and balanced out by hydropower, biomass and imports from the neighbouring countries.

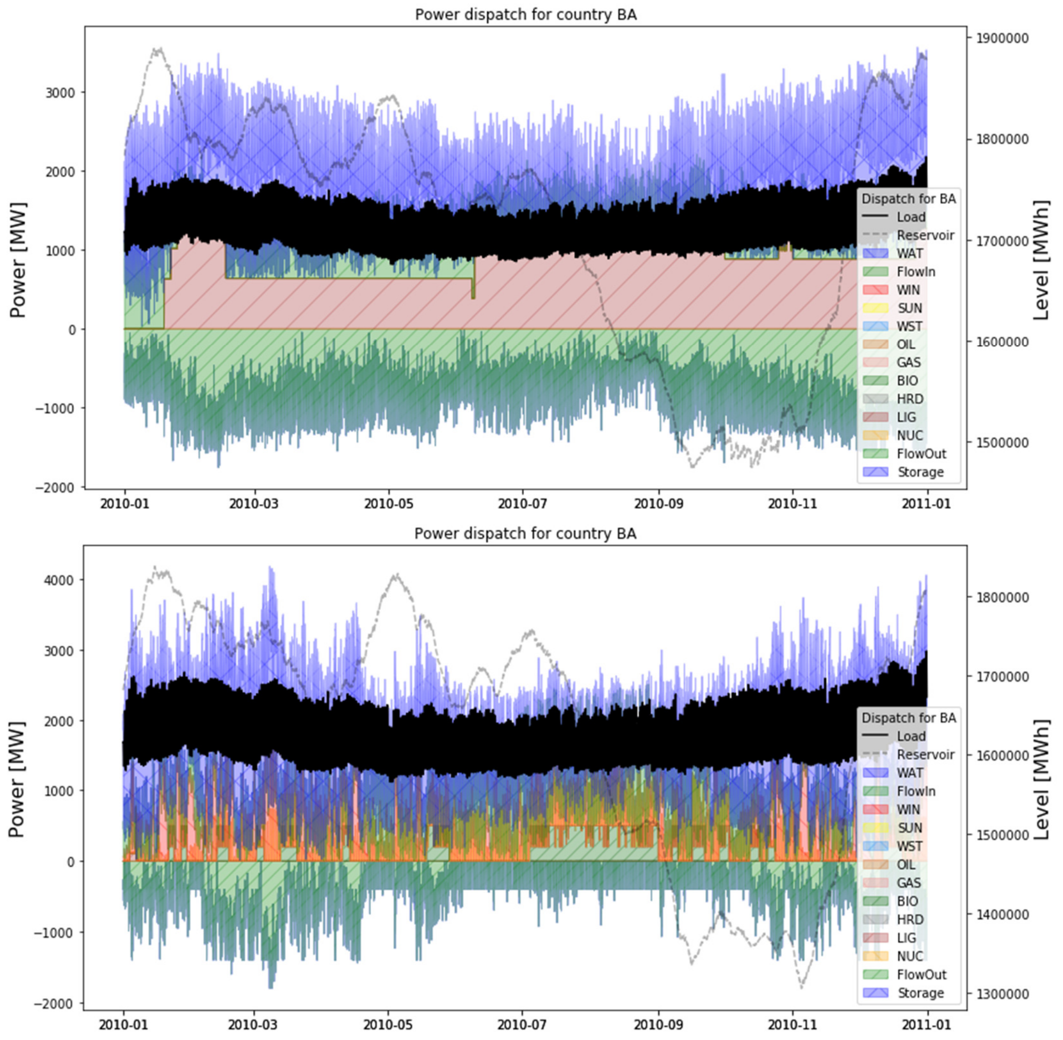


Figure 11. Annual power dispatch curves Reference scenario (top) and 2030 high RES scenario (bottom)

CONCLUSIONS

This article describes the implementation of the Dispa-SET model to the six Western Balkans countries of Albania, Bosnia and Herzegovina, Kosovo, Macedonia, Montenegro and Serbia. This implementation of the Dispa-SET can be freely downloaded† and is released with an open-source license to ensure transparency and reproducibility of the work [56].

Each of these six countries has its own power generating units, independent domestic electricity demands and is interconnected with the neighbouring countries through 210 and 400 kV transmission lines. A comprehensive open input dataset is provided for historical fuel prices, power plant data, planned and unplanned outages due to the power plant overhauls, river hydrology and weather data, historical cross-border energy flows and accumulation levels of all the available storage units. All this data has been statistically and mathematically processed and converted into a suitable format for the model.

In total, three scenarios, a reference one and two alternatives, have been developed. Due to the data availability, the year 2010 has been chosen as the Reference scenario and the best option for validating the model. The two alternative scenarios include two additional cases describing alternative future outcomes. The analysis of each of these six power sectors revealed the domination of lignite and hydropower and a relatively small share of gas, wind and solar in the total installed capacities. All these results have been compared with the real-world data and on average the total power generation in each zone and by each technology is within 10% of the historical data. The only exception is two neighbouring zones Kosovo and Montenegro where the deviation lies between 15 and 35%. The two alternative scenarios have been developed with the purpose of analysing the impact of future strategies and the integration of high shares of RES in the current power systems. Two cases inside each alternative scenario 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 an additional 11.7% and 28.7% of RES-E. The main indicator for validating the additional scenarios is the average price of electricity production calculated by the model. It has shown that the integration of RES-E can indeed lower the average cost of electricity in the region by up to 46.5%.

The results from this analysis have proven that all six countries have the potential to operate independently from the neighbouring countries even with a relatively high share of RES-E. This is an important fact as the integration of an additional 11.7% of RES-E by the year 2020 and 28.7% by the year 2030 would not compromise the stability of the regional power system. The results show that such high RES-E integration coupled with cross border interconnection expansion would rather increase the regions energy independence as well as the security of supply. Furthermore, a high share of RES-E would have a positive impact on reducing local air pollution and would lower GHG emissions by 47.3%. The potential problems of integrating such high shares of renewables are RES-E curtailment, load shedding and congestion in the transmission lines. These issues should be taken into account in the future planning of the power sectors in the region.

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† https://github.com/squoilin/Dispa-SET

NOMENCLATURE

$Committed_{i,u}$	committed status of unit at hour h {1 0} or integer	[-]
$CostFixed_{u}$	fixed costs	[EUR/h]
$CostLoadShedding_{i,n}$	shedding costs	[EUR/MWh]
$CostRampDown_{i,u}$	ramp-down costs	[EUR/MW]
$CostRampUp_{i,u}$	ramp-up costs	[EUR/MW]
$CostShutDown_{i,u}$	shut-down costs for one unit	[EUR/u]
$CostStartUp_{i,u}$	start-up costs for one un	[EUR/u]
$CostVariable_{i,u}$	variable costs	[EUR/MWh]
$Flow_{i,l}$	flow through lines	[MW]
$Power_{i,u}$	power output	[MW]
$PriceTransmission_{i,l}$	price of transmission between zones	[EUR/MWh]
$ShedLoad_{i,n}$	shed load	[MW]
$SystemCost$	total system cost	[EUR]

Subscripts and superscripts

i	time step in the current optimization horizon	[-]
l	transmission lines between nodes	[-]
n	zones	[-]
u	units	[-]

Abbreviations

AF	Availability Factor (0-1)
AL	Albania
BA	Bosnia and Herzegovina
BIO	Biomass/Biogas
CEEP	Critical Excess Electricity Production
CO_2	Carbon Dioxide
COMC	Combined Cycle
Dem	Electricity Demand
EU	European Union
GAS	Natural Gas
HDAM	Hydro Dam
HPHS	Pumped Hydro Storage
HRD	Hard Coal
HROR	Hydro Run of River
JRC	European Commission Joint Research Centre
LIG	Lignite
LP	Linear Programming
ME	Montenegro
MILP	Mixed Integer Linear Programming
MK	Macedonia
MPC	Model Predictive Control
MVP	Mean-Variance Portfolio
NTC	Net Transfer Capacity
NUC	Nuclear
OIL	Fuel Oil
PV	Solar Photovoltaics

RES-E	Energy From Renewable Energy Sources
RS	Serbia
STUR	Steam Turbine
SUN	Solar
TSO	Transmission System Operator
UCPD	Unit Commitment and Power Dispatch
VRE	Variable Renewable Energy
WAT	Water
WIN	Wind
WST	Waste
XK	Kosovo

REFERENCES

1. Energy Community (EnC), www.energy-community.org/aboutus/whoweare.html, [Accessed: 20-August-2017]
2. International Energy Agency (IEA), Energy in the Western Balkans: the Path to Reform and Reconstruction, Survey, p 207, Paris, France, 2008.
3. Pietrapertosa, F., Khokhlov, V., Salvia, M. and Cosmi, C., Climate Change Adaptation Policies and Plans: A Survey in 11 South East European Countries, *Renewable and Sustainable Energy Reviews*, Vol. 81, Part 2, pp 3041-3050, 2018, https://doi.org/10.1016/j.rser.2017.06.116
4. Energy Regulatory Authority of Albania, Power Sector Situation and the ERE's Activity for 2011, Annual Report, 2011.
5. Bosnia and Herzegovina, Statement on Security of Energy Supply of Bosnia and Herzegovina, Sarajevo, Bosnia and Herzegovina, 2011.
6. Republic of Macedonia, Statement on Security of Energy Supply of Republic of Macedonia, Skopje, Macedonia, 2011.
7. Ministry of Economy, Security of Supply Statement for Montenegro, Podgorica, Montenegro, 2011.
8. Ministry for Infrastructure and Energy, Security of Supply Statement of the Republic of Serbia, Beograd, Republic of Serbia, 2011.
9. Energy Regulatory Office, Statement of Security of Supply for Kosovo (Electricity, Natural Gas and Oil), Priština, Kosovo, 2011.
10. European Environment Agency, Energy Intensity, https://www.eea.europa.eu/data-and-maps/indicators/total-primary-energy-intensity-3, [Accessed: 11-February-2019]
11. Nielsen, H., Warde, P. and Kander, A., East versus West: Energy Intensity in Coal-rich Europe, 1800-2000, *Energy Policy*, Vol. 122, pp 75-83, 2018, https://doi.org/10.1016/j.enpol.2018.07.006
12. Maier, S. and Narodoslawsky, M., Optimal Renewable Energy Systems for Smart Cities, *Computer Aided Chemical Engineering*, Vol. 33, pp 1849-1854, 2014, https://doi.org/10.1016/B978-0-444-63455-9.50143-4
13. Lappe-Osthege, T. and Andreas, J. J., Energy Justice and the Legacy of Conflict: Assessing the Kosovo C Thermal Power Plant Project, *Energy Policy*, Vol. 107, pp 600-606, 2017, https://doi.org/10.1016/j.enpol.2017.03.006
14. Papapostolou, A., Karakosta, C., Nikas, A. and Psarras, J., Exploring Opportunities and Risks for RES-E Deployment under Cooperation Mechanisms Between EU and Western Balkans: A Multi-criteria Assessment, *Renewable and Sustainable Energy Reviews*, Vol. 80, pp 519-530, 2017, https://di.org/10.1016/j.rser.2017.05.190
15. Karakosta, C., Flouri, M., Dimopoulou, S. and Psarras, J., Analysis of Renewable Energy Progress in the Western Balkan Countries: Bosnia-Herzegovina and Serbia,

Renewable and Sustainable Energy Reviews, Vol. 16, No. 7, pp 5166-5175, 2012, https://doi.org/10.1016/j.rser.2012.04.040

16. Dunjic, S., Pezzutto, S. and Zubaryeva, A., Renewable Energy Development Trends in the Western Balkans, *Renewable and Sustainable Energy Reviews*, Vol. 65, pp 1026-1032, 2016, https://doi.org/10.1016/j.rser.2016.05.051
17. Dominković, D. F., Bačeković, I., Ćosić, B., Krajačić, G., Pukšec, T., Duić, N. and Markovska, N., Zero Carbon Energy System of South East Europe in 2050, *Applied Energy*, Vol. 184, pp 1517-1528, 2016, https://doi.org/10.1016/j.apenergy.2016.03.046
18. Cebulla, F., Naegler, T. and Pohl, M., Electrical Energy Storage in Highly Renewable European Energy Systems: Capacity Requirements, Spatial Distribution, and Storage Dispatch, *Journal of Energy Storage*, Vol. 14, Part 1, pp 211-223, 2017, https://doi.org/10.1016/j.est.2017.10.004
19. Koltsaklis, N. E. and Nazos, K., A Stochastic MILP Energy Planning Model Incorporating Power Market Dynamics, *Applied Energy*, Vol. 205, pp 1364-1383, 2017, https://doi.org/10.1016/j.apenergy.2017.08.040
20. Pleßmann, G. and Blechinger, P., Outlook on South-East European Power System Until 2050: Least-cost Decarbonization Pathway Meeting EU Mitigation Targets, *Energy*, Vol. 137, pp 1041-1053, https://doi.org/10.1016/j.energy.2017.03.076
21. Batas Bjelić, I., Rajaković, N., Ćosić, B. and Duić, N., Increasing Wind Power Penetration into the Existing Serbian Energy System, *Energy*, Vol. 57, pp 30-37, 2013, https://doi.org/10.1016/j.energy.2013.03.043
22. Batas Bjelić, I., Rajaković, N., Krajačić, G. and Duić, N., Two Methods for Decreasing the Flexibility Gap in National Energy Systems, *Energy*, Vol. 115, Part 3, pp 1701-1709, 2016, https://doi.org/10.1016/j.energy.2016.07.151
23. Dimitrijevic, Z. and Salihbegovic, I., Sustainability Assessment of Increasing Renewable Energy Sources Penetration – JP Elektroprivreda B&H Case Study, *Energy*, Vol. 47, No. 1, pp 205-212, 2012, https://doi.org/10.1016/j.energy.2012.09.010
24. Ostojic, G., Stankovski, S., Ratkovic, Z., Miladinovic, L. and Maksimovic, R., Development of Hydro Potential in Republic Srpska, *Renewable and Sustainable Energy Reviews*, Vol. 28, pp 196-203, 2013, https://doi.org/10.1016/j.rser.2013.07.036
25. Višković, V., Chen, Y. and Siddiqui, A. S., Implications of the EU Emissions Trading System for the South-East Europe Regional Electricity Market, *Energy Economics*, Vol. 65, pp 251-261, 2017, https://doi.org/10.1016/j.eneco.2017.04.033
26. Dokic, S. B. and Rajakovic, N. L., Security Modelling of Integrated Gas and Electrical Power Systems by Analyzing Critical Situations and Potentials for Performance Optimization (in press), *Energy*, 2018, https://doi.org/10.1016/j.energy.2018.04.165
27. Novacheck, J. and Johnson, J. X., Diversifying Wind Power in Real Power Systems, *Renewable Energy*, Vol. 106, pp 177-185, 2017, https://doi.org/10.1016/j.renene.2016.12.100
28. Đukan, M. and Aralica, Z., Analysing a Bottom-up Methodology for Developing Communal Biogas Plants in Croatia, *Journal of Sustainable Development of Energy, Water and Environment Systems*, Vol. 3, No. 2, pp 359-371, 2015, https://doi.org/10.13044/j.sdewes.2015.03.0027
29. Katsaros, G., Nguyen, T.-V. and Rokni, M., Tri-generation System Based on Municipal Waste Gasification, Fuel Cell and an Absorption Chiller, *Journal of Sustainable Development of Energy, Water and Environment Systems*, Vol. 6, No. 1, pp 13-32, 2017, https://doi.org/10.13044/j.sdewes.d5.0172
30. Leobner, I., Smolek, P., Heinzl, B., Raich, P., Schirrer, A., Kozek, M., Rossler, M. and Morzinger, B., Simulation-based Strategies for Smart Demand Response,

Journal of Sustainable Development of Energy, Water and Environment Systems, Vol. 6, No. 1, pp 33-46, 2017, https://doi.org/10.13044/j.sdewes.d5.0168

31. Pfenninger, S., Hirth, L., Schlecht, I., Schmid, E., Wiese, F., Brown, T., Davis, C., Gidden, M., Heinrichs, H., Heuberger, C., Hilpert, S., Krien, U., Matke, C., Nebel, A., Morrison, R., Müller, B., Pleßmann, G., Reeg, M., Richstein, J. C., Shivakumar, A., Staffell, I., Tröndle, T. and Wingenbach, C., Opening the Black Box of Energy Modelling: Strategies and Lessons Learned, *Energy Strategy Reviews*, Vol. 19, pp 63-71, 2018, https://doi.org/10.1016/j.esr.2017.12.002
32. Quoilin, S., Hidalgo Gonzalez, I. and Zucker, A., Modelling Future EU Power Systems Under High Shares of Renewables: The Dispa-SET 2.1 Open-source Model, Scientific and Technical Research Reports, Publications Office of the European Union, 2017, https://doi.org/10.2760/25400
33. Arroyo, J. M. and Conejo, A. J., Optimal Response of a Thermal Unit to an Electricity Spot Market, *IEEE Transactions on Power Systems*, Vol. 15, No. 3, pp 1098-1104, 2000, https://doi.org/10.1109/59.871739
34. Carrion, M. and Arroyo, J. M., A Computationally Efficient Mixed-Integer Linear Formulation for the Thermal Unit Commitment Problem, *IEEE Transactions on Power Systems*, Vol. 21, No. 3, pp 1371-1378, 2006, https://doi.org/10.1109/TPWRS.2006.876672
35. Morales-españa, G., Latorre, J. M. and Ramos, A., Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem, *IEEE Transactions on Power Systems*, Vol. 28, No. 4, pp 4897-4908, 2013, https://doi.org/10.1109/TPWRS.2013.2251373
36. Jovanović, L. and Cvijić, L., The Project Activities of the Renewable Energy Resources Use in the Republic of Serbia, *Journal of Sustainable Development of Energy, Water and Environment Systems*, Vol. 2, No. 3, pp 234-242, 2014, https://doi.org/10.13044/j.sdewes.2014.02.0019
37. Ćosić, B., Krajačić, G. and Duić, N., A 100% Renewable Energy System in the Year 2050: The Case of Macedonia, *Energy*, Vol. 48, No. 1, pp 80-87, 2012, https://doi.org/10.1016/j.energy.2012.06.078
38. Ćosić, B., Markovska, N., Krajačić, G., Taseska, V. and Duić, N., Environmental and Economic Aspects of Higher RES Penetration into Macedonian Power System, *Applied Thermal Engineering*, Vol. 43, pp 158-162, 2012, https://doi.org/10.1016/j.applthermaleng.2011.10.042
39. Burlando, M., Podesta, A., Villa, L., Ratto, C. F. and Cassulo, G., Preliminary Estimate of the Large-scale Wind Energy Resource with Few Measurements Available: The Case of Montenegro, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 97, No. 11-12, pp 497-511, 2009, https://doi.org/10.1016/j.jweia.2009.07.011
40. Bekteshi, S., Kabashi, S., Ahmetaj, S., Šlaus, I., Zidanšek, A., Podrimqaku, K. and Kastrati, S., Dynamic Modeling of Kosovo's Electricity Supply-Demand, Gaseous Emissions and Air Pollution, *Journal of Sustainable Development of Energy, Water and Environment Systems*, Vol. 3, No. 3, pp 303-314, 2015, https://doi.org/10.13044/j.sdewes.2015.03.0023
41. Jeffers, B., South East Europe: The EU Road or the Road to Nowhere? An Energy Roadmap for 2050: A Guide to the Future, South East Europe Sustainable Energy Policy, Report, 2016.
42. Kovacevic, A., Fossil Fuel Subsidies in the Western Balkans, A Report for UNDP, Regional Bureau for Europe and the Commonwealth of Independent States (RBEC), 2011.
43. Hystoric Gas Prices, https://ycharts.com/indicators/europe_natural_gas_price, [Accessed: 01-June-2016]

44. Pfeifer, A., Dominković, D. F., Ćosić, B. and Duić, N., Economic Feasibility of CHP Facilities Fueled by Biomass from Unused Agriculture Land: Case of Croatia, *Energy Conversion and Management*, Vol. 125, pp 222-229, 2016, https://doi.org/10.1016/j.enconman.2016.04.090
45. Hentschel, J., Babić, U. and Spliethoff, H., A Parametric Approach for the Valuation of Power Plant Flexibility Options, *Energy Reports*, Vol. 2, pp 40-47, 2016, https://doi.org/10.1016/j.egyr.2016.03.002
46. Schill, W.-P., Pahle, M. and Gambardella, C., On Start-Up Costs of Thermal Power Plants in Markets with Increasing Shares of Fluctuating Renewables, *DIW Discussion Papers*, Vol. 1540, pp 24, 2016.
47. Pfenninger, S. and Staffell, I., Long-term Patterns of European PV Output using 30 Years of Validated Hourly Reanalysis and Satellite Data, *Energy*, Vol. 114, pp 1251-1265, 2016, https://doi.org/10.1016/j.energy.2016.08.060
48. Šúri, M., Huld, T. A. and Dunlop, E. D., PV-GIS: A Web-based Solar Radiation Database for the Calculation of PV Potential in Europe, *International Journal of Solar Energy*, Vol. 24, No. 2, pp 55-67, 2005, https://doi.org/10.1080/14786450512331329556
49. European Network of Transmission System Operators (ENTSO-E), Indicative Values for Net Transfer Capacities (NTC) in Europe – 2010 2011, https://www.entsoe.eu/fileadmin/user_upload/_library/ntc/archive/NTC-Values-Winter-2010-2011.pdf, [Accessed: 18-August-2018]
50. Kosovar Transmission System Operator (KOSTT), List of New Transmission Capacities and Interconnection Lines (2011-2020), Priština, Kosovo, 2011.
51. European Network of Transmission System Operators (ENTSO-E), ENTSO-E Transmission System Map, https://www.entsoe.eu/data/map/, [Accessed: 11-August-2018]
52. Verboomen, J., Spaan, F. J. C. M., Schavemaker, P. H. and Kling, W. L., Method for Calculating Total Transfer Capacity by Optimising Phase Shifting Transformer Settings, Conference Paper, CIGRE, Paris, France, 2008.
53. European Network of Transmission System Operators (ENTSO-E) Transparency Platform.
54. Elektroprivreda Srbije, Production Indicators PD TENT – 2010 (in Serbian), Beograd, Republic of Serbia, 2010.
55. Nezavisni Operater Sistema u Bosni i Hercegovini (NOSBiH), Electricity Factor Report on the Transmission Grid in BiH (in Bosnian), Sarajevo, Bosnia and Herzegovina, 2011.
56. Pfenninger, S., DeCarolis, J., Hirth, L., Quoilin, S. and Staffell, I., The Importance of Open Data and Software: Is Energy Research Lagging Behind?, *Energy Policy*, Vol. 101, pp 211-215, 2017, https://doi.org/10.1016/j.enpol.2016.11.046
57. JP Elektroprivreda Hrvatske Zajednice Herceg Bosne (JP EHZHB), 30 Years of CHE Čapljina (in Bosnian), Sarajevo, Bosnia and Herzegovina, 2009.
58. HE na Drini | Višegrad, HE na Drini, https://www.henadrini.com/, [Accessed: 11-August-2018]
59. Nezavisni Operater Sistema u Bosni i Hercegovini (NOSBiH), Starting the Power Plant without the Presence of an External Voltage – A Study (in Bosnian), Sarajevo, Bosnia and Herzegovina, 2009.
60. HE na Trebišnjici | Elektroprivreda Republike Srpske, https://ers.ba/ers/profil/zavisna-preduzeca/he-na-trebisnjici/, [Accessed: 11-August-2018]
61. Milivojević, N., Kašiković, M. and Krunić, G., Energy Performance and Energy Indicators in the MH ERS a.d. Trebinje System (in Bosnian), *Proceedings of the 17th International Symposium INFOTEH-JAHORINA*, p 6, Jahorina, Bosnia and Herzegovina, 2018.

62. JP Elektroprivreda Hrvatske Zajednice Herceg Bosne (EPHZHB), Year Report – 2010, Mostar, Bosnia and Herzegovina, 2010.
63. Hidroelektrane na Vrbasu, http://www.henavrbasu.com/hev/DefaultLang.aspx?lang=cir&lang2=lat, [Accessed: 11-August-2018]
64. HE Dubrovnik, HEP Proizvodnja, http://proizvodnja.hep.hr/proizvodnja/osnovni/hidroelektrane/dubrovnik/default.aspx, [Accessed: 11-August-2018]
65. JP Elektroprivreda Hrvatske Zajednice Herceg Bosne (EPHZHB), HE Mostar – Brochure (in Bosnian), Mostar, Bosnia and Herzegovina, 2010.
66. Elektroprivreda Crne Gore AD Nikšić, EPCG – Proizvodni Objekti, https://www.epcg.com/o-nama/proizvodni-objekti, [Accessed: 12-August-2018]
67. United Nations Framework Convention on Climate Change (UNFCCC), Form of Draft Project Proposal (CDM-SSC-PDD) – Version 03 (in Bosnian), 2006.
68. Drinsko-Limske Hidroelektrane, http://dlhe.rs/latinica, [Accessed: 12-August-2018]
69. HE Djerdap, http://www.djerdap.rs/sr, [Accessed: 12-August-2018]
70. JP Elektroprivreda Hrvatske Zajednice Herceg Bosne (EPHZHB), HE Jajce I, Jajce II – Brochure (in Bosnian), Mostar, Bosnia and Herzegovina, 2011.
71. Elektroprivreda Srbije (EPS), MHE Cadastre in Serbia 2015 (in Serbian).

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ANNEX A

Table 5. Technical characteristics of the HDAM power plants in the year 2010

		Dam			Accumulation		
Unit	Zone	Power [MW]	Flow [m^3/s]	Head [M]	Volume [10^3 m^3]	Energy [MWh]	Ref.
HE Fierza	AL	500	4,665	118.0	2,300,000	739,565	[4]
HE Koman	AL	600	736.0	96.0	188,000	49,180	
HE Vau Dejes	AL	250	565.0	52.0	263,000	37,267	
HE Ulez	AL	25	64.0	54.0	124,000	18,246	
HE Shkopetit	AL	24	80.0	38.5	15,000	1,573	
RHE Capljina	BA	420	225.0	228.0	6,500	3,400	[57]
HE Visegrad	BA	315	800.0	43.0	161,000	18,865	[58]
HE Salakovac	BA	210	540.0	42.0	68,000	7,783	[59]
HE Jablanica	BA	181	208.8	94.0	288,000	73,536	
HE Trebinje 1	BA	168	210.0	104.0	1,070,000	1,010,700	[60, 61]
HE Rama	BA	160	64.0	285.0	466,000	303,000	[62]
HE Bocac	BA	110	240.0	55.0	42,900	5,322	[63]
HE Dubrovnik	BA	108	45.0	272.0	1,110,000	821,991	[64]
HE Mostar	BA	72	360.0	24.0	10,920	714	[65]
HE Trebinje 2	BA	8	45.0	22.0	9,600	6,037	[60, 61]
HE Piva	ME	360	240.0	150.0	880,000	359,700	[7, 66]
HE Perucica	ME	310	68.0	549.0	148,000	221,412	
HE Pljevlja	ME	3	9.0	43.0	18,000	2,109	[7, 67]
HE Vrutok	MK	150	32.0	525.0	227,000	324,751	[6]
HE Tikvesh	MK	114	144.0	91.3	309,600	77,026	
HE Shpilje	MK	84	108.0	85.2	223,000	51,773	
HE Kozjak	MK	80	100.0	92.0	260,000	65,182	
HE Globocica	MK	42	50.0	95.0	13,200	3,427	
RHE Bajina Basta	RS	614	129.2	555.0	170,000	194,000	[8, 68]
HE Bistrica	RS	102	36.0	378.3	7,600	7,834,593	
HE Pirot	RS	80	45.0	243.0	180,000	75,000	[8, 69]
HE Potpec	RS	54	165.0	38.4	25,000	2,616	[8, 68]
HE Vrla 1-4	RS	51	18.3	338.0	165,000	198,000	[8, 69]
HE Uvac	RS	36	43.0	100.0	213,000	34,000	[8, 68]
HE Kokin Brod	RS	22	37.4	72.0	210,000	202,000	
HE Ujmani	XK	35	35.7	100.0	350,000	95,375	[9]

Table 6. Technical characteristics of the HROR power plants in the year 2010

Unitname	Zone	Power [MW]	Flow rate [m^3/s]	Ref.
HE Bistrica 1	AL	22.50	8.50	[4]
HE Bistrica 2	AL	5.00	0.08	
HE Borsh	AL	0.25	0.02	
HE Kerpice	AL	0.42	1.00	
HE Dukagjin	AL	0.64	68.51	
HE Arras	AL	4.80	430.47	
HE Homesh	AL	0.33	2.18	
HE Orenje	AL	0.88	336.96	
HE Funares	AL	1.92	99.77	
HE Selce	AL	2.15	242.33	
HE OrgjosiRi	AL	4.80	377.69	
HE Tucep	AL	1.70	195.96	
HE Lenia	AL	0.40	0.10	
HE Bogova	AL	2.50	28.05	
HE Leskovik	AL	1.07	5.00	
HE Smokthina	AL	9.00	16.70	
HE Treske 2	AL	0.25	4.34	
HE Velcan	AL	1.20	304.34	
HE Tervol	AL	10.60	120.06	
HE Grabovica	BA	114.00	380.00	[5, 59]
HE Mostarsko Blato	BA	60.00	36.00	[5, 65]
HE Jajce 1	BA	60.00	74.00	[5, 70]
HE Jajce 2	BA	30.00	79.80	
HE Pec Mlini	BA	30.60	30.00	[5, 62]
HE Bogatici	BA	9.40	88.00	[5, 61]
HE Vlasenica	BA	1.08	1.75	
HE Mesica Nova	BA	5.77	5.00	
HE Bistrica B-5 A	BA	4.90	8.00	[5, 68]
HE Majdan	BA	3.87	2.00	[5]
HE Botun	BA	2.64	1.60	
HE Jezernica	BA	1.54	0.94	
HE Mujakovici	BA	1.90	15.00	
HE Modrac	BA	1.04	1.13	
HE Tresanica T-4	BA	1.30	0.45	
HE Osanica	BA	1.23	1.35	
HE Novakovici	BA	7.00	5.50	
HE Una Kostela	BA	0.90	0.70	
HE Glava Zete	ME	5.36	29.00	[7]
HE Slap Zete	ME	1.20	26.00	
HE Muskovica Rijeka	ME	0.84	0.70	
HE Savnik	ME	0.20	1.00	
HE Lijeva Rijeka	ME	0.06	0.22	
HE Podgor	ME	0.40	0.90	
HE Rijeka Crnojevica	ME	0.56	3.00	
Unit	Zone	Power [MW]	Flow rate [m^3/s]	Ref.
HE Raven	MK	19.20	28.00	[6]
HE Vrben	MK	12.80	8.00	
HE Matka	MK	8.00	40.00	
HE Dosnica	MK	4.10	8.00	
HE Kalimanci	MK	13.80	19.05	
HE Pesocani	MK	2.70	5.00	
HE Popova sapka	MK	4.80	9.06	
HE Penacascade	MK	2.50	9.09	
HE Sapuncica	MK	2.90	3.78	
HE Strezevo 1	MK	3.40	6.80	
HE Turija	MK	2.20	5.14	
HE Zrnovci	MK	1.40	35.09	
HE Bajina Basta G4	RS	364.00	692.00	[8, 68]
HE Derdap 2	RS	270.00	4.20	[8, 69]
HE Derdap 1	RS	1,058.00	4,800.00	
HE Seljasnica	RS	0.90	0.75	[8]
HE Sicevo	RS	1.34	12.00	[8 ,71]
HE Sokolovica	RS	5.20	40.00	
HE Vlasontice	RS	1.50	4.00	
HE Ostrovica	RS	1.11	9.00	
HE Zvornik	RS	96.00	620.00	[8, 68]
HE Medjuvrsje	RS	7.00	20.00	
HE Ovčar Banja	RS	6.00	20.00	
HE Lumbardhi	XK	8.80	112.00	[9]
HE Dikance	XK	1.34	41.00	
HE Radavac	XK	0.33	215.00	
HE Burimi	XK	0.55	41.00	

Table 7. Technical data of the thermal power plants in the year 2010

Unit	Zone	Techology/Fuel	Power [MW]	Eff. [%]	Start up time [h]	Min. up time [h]	Min. down time [h]	Ramp rates [%/min]	Min. part load [%]	CO$_2$ intensity [kg/MWh]	Ref.
TE Vlora	AL	STUR/OIL	98	35.0	3	2	2.0	6	12.9	517	[4]
TE Tuzla	BA	STUR/LIG	630	34.2	6	6	1.5	2.5	5.4	1,062	[5]
TE Kakanj	BA	STUR/LIG	385	34.2	6	6	1.5	2.5	8.8	1,062	
TE Ugljevik	BA	STUR/LIG	264	34.0	6	6	1.5	2.5	40.0	1,062	
TE Gacko	BA	STUR/LIG	255	34.1	6	6	1.5	2.5	40.0	1,062	
TE Pljevlja	ME	STUR/LIG	210	34.3	6	6	1.5	2.5	40.0	1,062	[7, 66]
TE Bitola	MK	STUR/LIG	699	34.0	6	6	1.5	2.5	13.3	1,062	[6]
TE Oslomej	MK	STUR/LIG	125	34.0	6	6	1.5	2.5	40.0	1,062	
TE Kolubara	RS	STUR/LIG	245	34.2	6	6	1.5	2.5	5.2	1,062	[8, 54]
TE Kostolac A	RS	STUR/LIG	281	34.0	6	6	1.5	2.5	12.8	1,062	
TE Kostolac B	RS	STUR/LIG	640	34.0	6	6	1.5	2.5	20.0	1,062	
TE Morava	RS	STUR/LIG	108	34.0	6	6	1.5	2.5	40.0	1,062	
TE Nikola Tesla A	RS	STUR/LIG	1,502	34.1	6	6	1.5	2.5	5.6	1,062	
TE Nikola Tesla B	RS	STUR/LIG	1,160	34.1	6	6	1.5	2.5	18.6	1,062	
TETO Novi Sad	RS	COMC/GAS	208	57.0	3	2	2.0	6.0	21.2	398	
TETO Zrenjanin	RS	COMC/GAS	100	57.0	3	2	2.0	6.0	45.0	398	
TETO Sremska Mitrovica	RS	COMC/GAS	45	57.0	3	2	2.0	6.0	15.0	398	
TE Kosovo A	XK	STUR/LIG	395	34.0	6	6	1.5	2.5	14.8	1,062	[9]
TE Kosovo B	XK	STUR/LIG	520	34.1	6	6	1.5	2.5	22.5	1,062	

ANNEX B

Wind

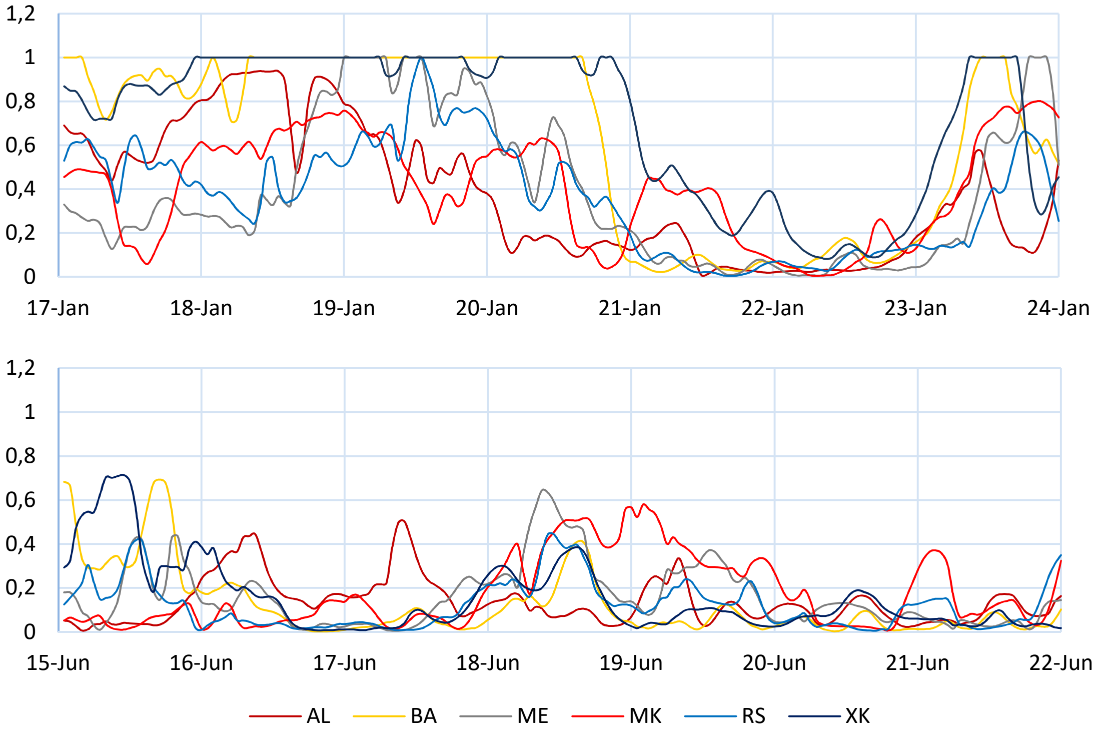

Figure 12. Wind availability factors during the 7-day period in January and June

Solar

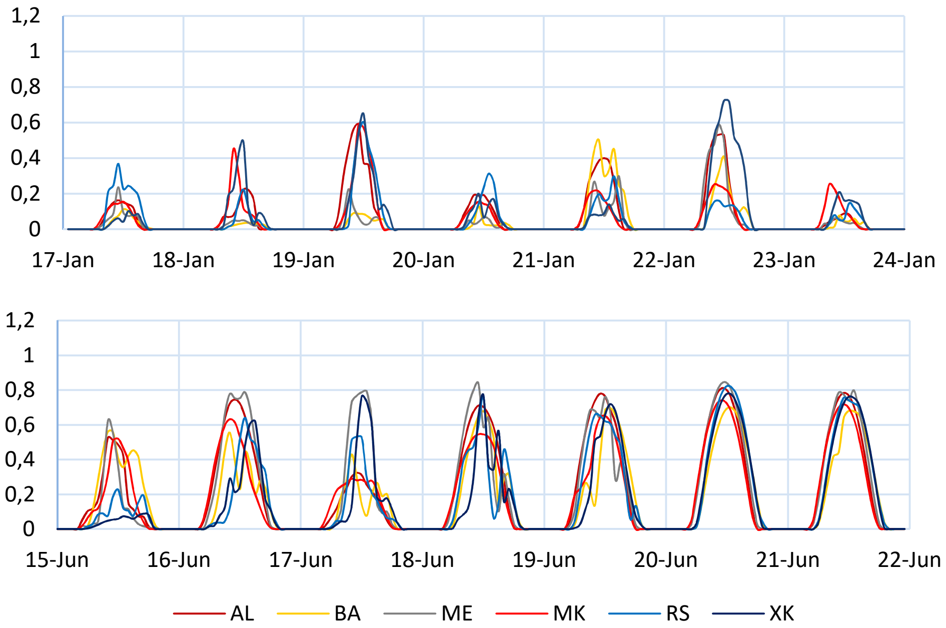

Figure 13. Solar availability factors during the 7-day period in January and June

ANNEX C

Reference scenario

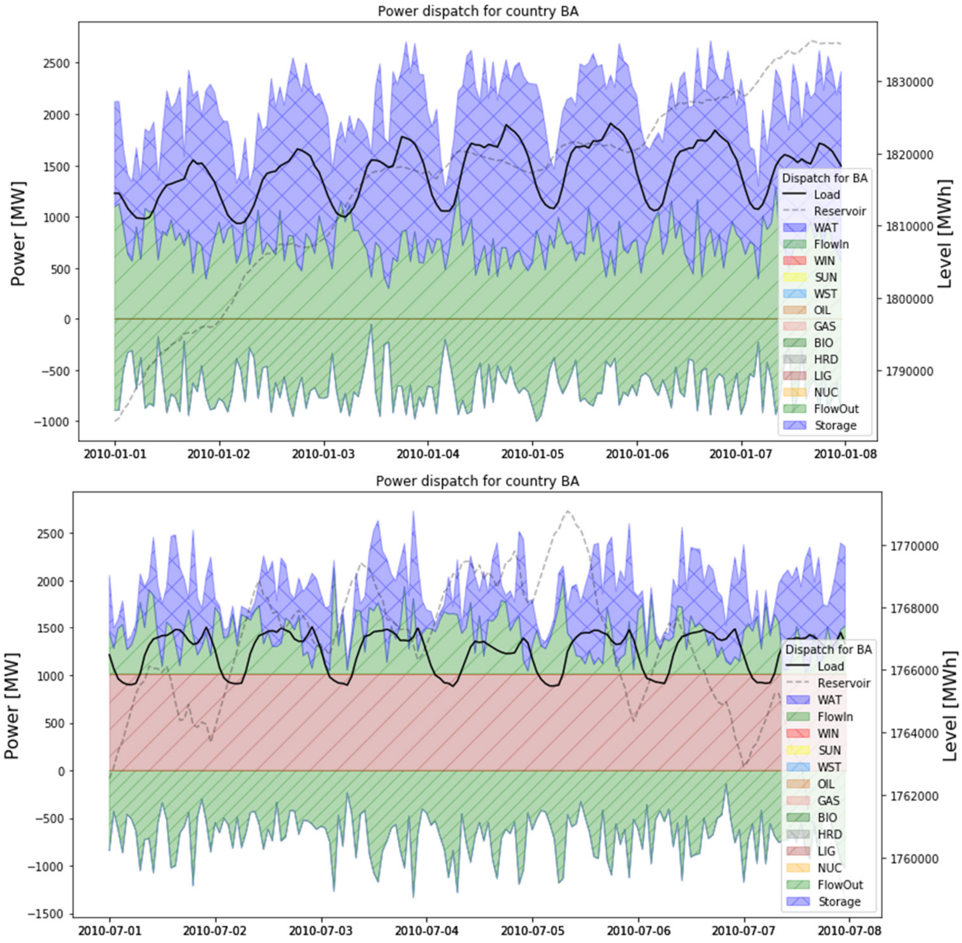

Figure 14. Weekly power dispatch curves from Reference scenario in January and July

2020 scenario – Case A

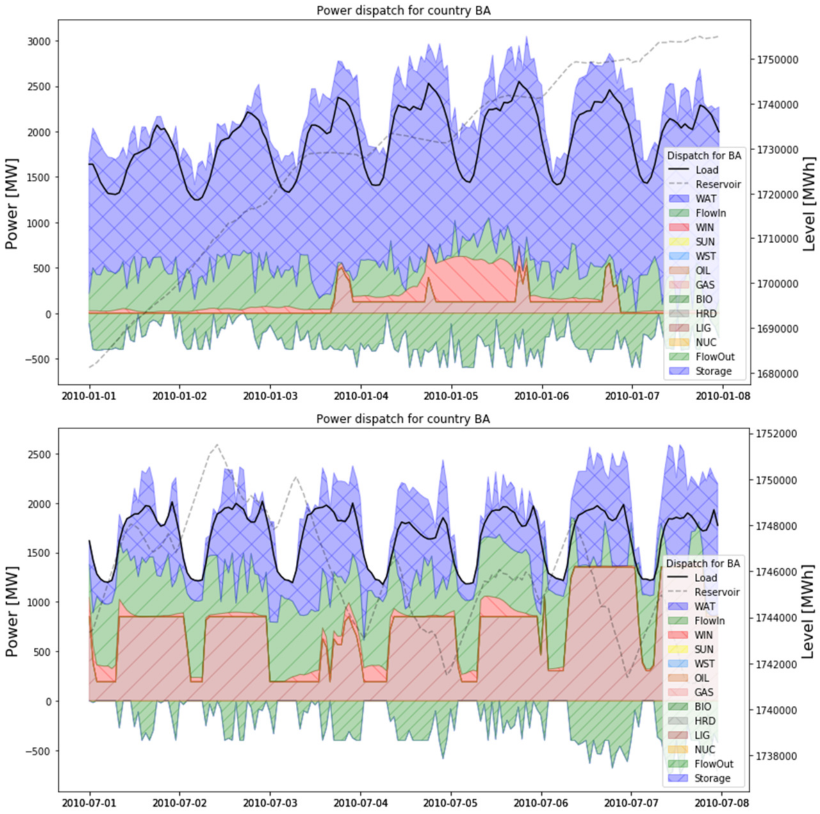

Figure 15. Weekly power dispatch curves from 2020 scenario – Case A in January and July

High Electricity from Renewable Energy Sources 2020 scenario – Case B

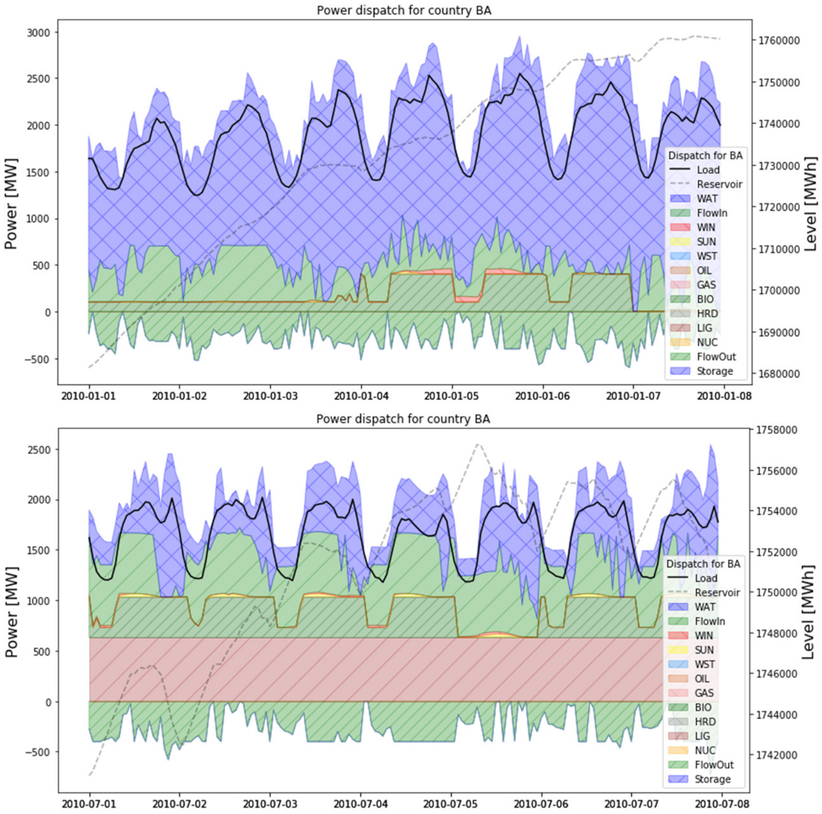

Figure 16. Weekly power dispatch curves from High RES-E 2020 scenario – Case B in January and July

2030 scenario – Case C

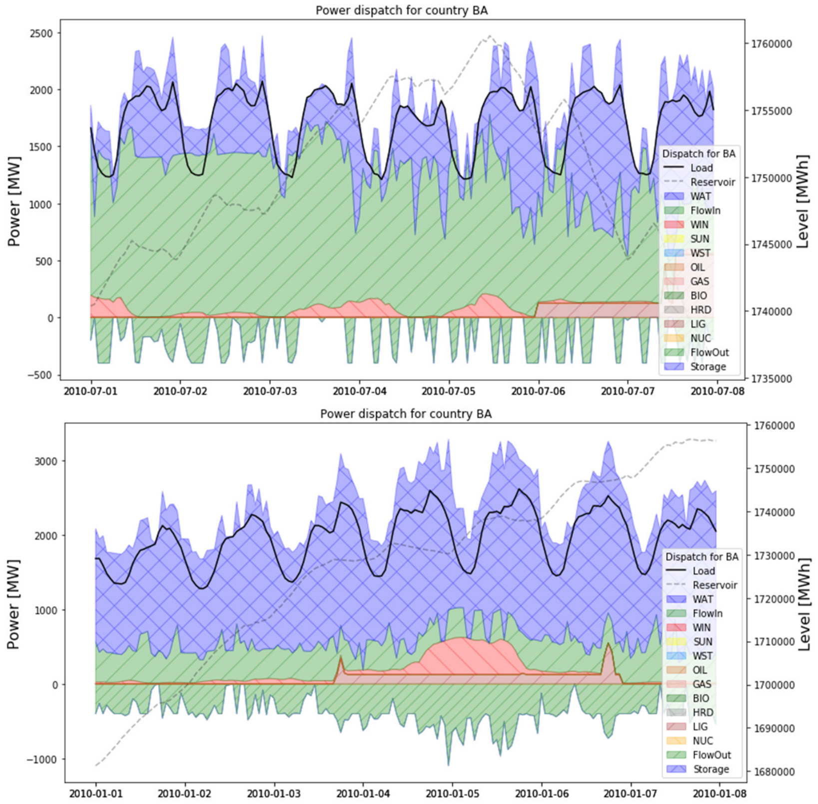

Figure 17. Weekly power dispatch curves from 2030 scenario – Case C in January and July

High Electricity from Renewable Energy Sources 2030 scenario – Case D

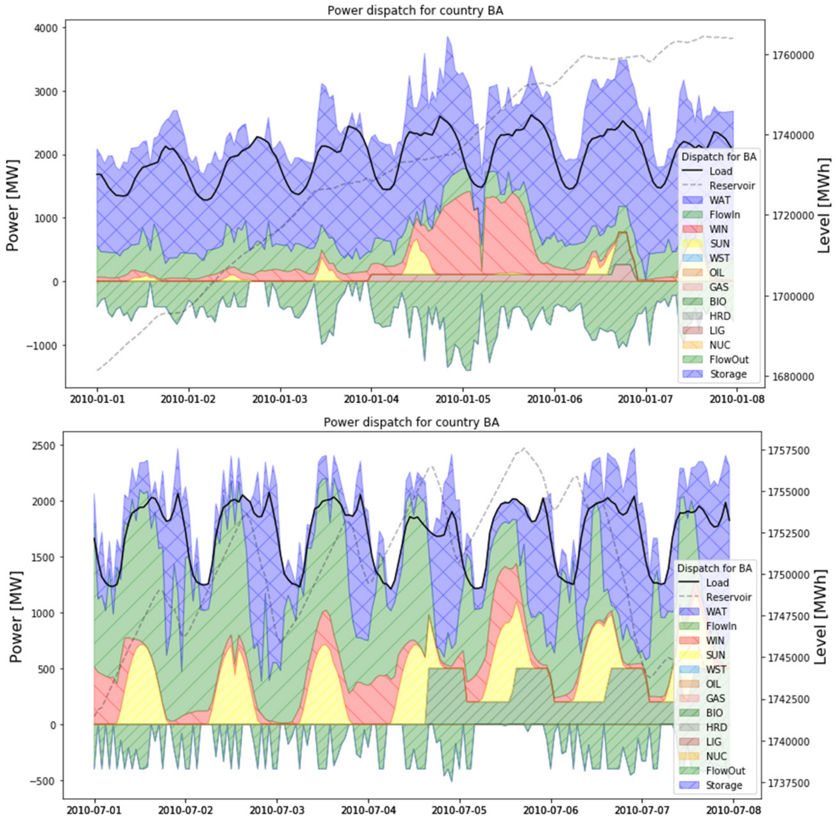

Figure 18. Weekly power dispatch curves from High RES-E 2030 scenario – Case D in January and July