IMPACT OF REVITALIZATION OF EXISTING AND BUILDING OF NEW HYDROPOWER PLANTS ON UNCONSTRAINED PENETRATION OF RES: REGIONAL CASE OF SE EUROPEAN COUNTRIES

UTJECAJ REVITALIZACIJE POSTOJEĆIH I IZGRADNJE NOVIH HIDROELEKTRANA NA NEOMETANU PENETRACIJU OIE: REGIONALNI SLUČAJ ZEMALJA JI EUROPE

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Rad po pozivu

<https://doi.org/10.240/ptk.018.30.1.209>

The global problem in the form of climate change is increasingly evident. The consensus of the world's scientific and expert community is that today's human action, primarily regarding greenhouse gas emissions, is one of the key reasons for accelerating the negative effects, primarily the rise in average temperature on Earth. One of the solutions to reduce CO₂ emissions from the power generation sector, which is one of the most significant greenhouse gas emitters, is the intensified penetration of renewable energy sources. This paper will examine the impact of increasing capacities in reservoir and pumped storage hydropower plants, as well as the revitalization of existing hydropower plants on the possibility of unconstrained penetration of renewable energy sources, primarily wind, based on the developed regional model. Namely, due to its intermittent nature wind energy requires additional flexibility in the system, and hydro power plants are one of the best providers of such services currently, especially in the region of SE Europe. On the other hand, hydropower plants usually have high investment costs.

Key words: climate changes, regional model; SE European countries; hydropower plan revitalization; system flexibility

Globalni svjetski problem u vidu klimatskih promjena sve je očitiji. Konsenzus svjetske znanstvene i stručne zajednice je da današnje djelovanje čovjeka, prvenstveno emisijama stakleničkih plinova, na okolinu jedan od ključnih razloga za ubrzavanje negativnih efekata, prije svega porasta prosječne temperature na Zemlji. Jedno od rješenja za smanjenje CO₂ emisija iz elektroenergetskog sektora, koji je među najznačajnijim emiterima stakleničkih plinova, je pojačana penetracija obnovljivih izvora energije. U radu će se na temelju izrađenog regionalnog modela ispitati utjecaj povećanja kapaciteta u akumulacijskim i reverzibilnim hidroelektranama, kao i revitalizacije postojećih hidroelektrana na mogućnost neometane penetracije obnovljivih izvora energije, prije svega vjetra. Naime, zbog intermitentne prirode energija vjetra zahtijeva dodatnu fleksibilnost u sustavu, a hidroelektrane su jedan od najboljih pružatelja takvih usluga trenutno, posebice u regiji zemalja JI Europe. Mana su im visoki investicijski troškovi.

Ključne reči: klimatske promjene; regionalni model; zemlje JI Europe; revitalizacija hidroelektrana; fleksibilnost sustava

1 Introduction

One of the first global efforts made in order to prevent large future issues for mankind and all other living forms was fight to secure protective ozone layer in the atmosphere. Solutions and agreements that have been made during last few decades in that direction are showing good results at present time. In the meanwhile, mankind has become aware of yet another global issue - global warming in the scope of climate change process. Global consensus is that greenhouse gases (GHGs) emissions are considered to be the main cause of climate changes. One of largest GHG emitters is power system sector, especially thermal power plants that use fossil fuels [1]. These power plants generate around 66% of total world electricity needs [2].

Investments in assets within power system are usually very intensive and are characterized as typical example of economy of scale. Deregulated electricity market price uncertainty imposes even greater risk on

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new investors and profit made on electricity market also have to cover the initial investment. On the other hand, main goal of power system is to satisfy electricity load at any point of time.

Worldwide energy development strategies encourage the development of RES based on the climate change agreements. Concept of sustainable development is one of key solutions to tackle climate changes. It promotes sustainable future that requires transition from fossil fuel-based power system towards power system based on renewable energy sources (RES). One of suitable definitions of sustainable development is: *“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”* [3]. As an upgrade of Kyoto protocol [4] a new agreement that supports sustainable development worldwide has been reached in 2015 - Paris Agreement [5]. It is long-term, mutual, ambitious, transparent and solidary project with main goal to limit global warming below 2 °C by proposed measures especially promotion of RES.

Due to its well-developed technology and already used significant available potential traditional large hydropower plants are usually not considered as RES. Therefore, wind power plants and photovoltaic (PV) power plants are currently predominant RES sources of electricity worldwide. Besides novel technology and still questionable grid parity main issue of these sources is their intrinsic variability and intermittency that has great negative potential to decrease power system stability and also affect its operation [6]. In addition to technical issues large financial burden in terms of increased power system balancing cost [7]. Besides intermittency RES power plants are usually also geographically unevenly distributed and situated far away from load centers.

Aforementioned issues are present regardless of time frame (short-term to long-term) and resolution (minute, hour, week etc.) in concern. There are numerous efforts and forecasting methods related to wind and PV power plants outputs and some of them are well developed [8], [9]. At the same time there is at some extent unavoidable forecasting errors (difference between forecasted and realized generation) in RES generation with intrinsic variability (such as wind and PV generation). [10]. With increasing RES power plant capacity penetration this error become more evident, especially in absolute terms. In cases of very high RES penetration level additional issues can arise in those moments when there is excess RES generation available, in other words RES generation alone is able to supply total load of observed system [11]. One possible solution for this issue is to curtail RES generation and it can be understood as wasting of valuable source of energy. The other, more attractive, solution is to store that excess energy in energy storage systems (ESS), if such are available at particular time and location. Having in mind all previously stated the best solution for this issue can be additional flexible generation capable of energy storage such as pumped-storage hydroelectricity (PSH) or hydropower plants (HPP) [12], [13], [14]. One solution that is becoming more and more investigated but still not highly used in practice are heat energy storage systems (HESS) as a way of coupling power system and district heating systems (DHS).

This paper will focus on PSH and HPP role in providing support to larger penetration of RES in countries in SE Europe region, more specifically Croatia, Serbia, Montenegro and Bosnia and Herzegovina. PSH role is expected to be of greater importance than role of HPP due to fact that these plants are able to consume electricity during periods of RES abundance and produce electricity in peak load periods. The main question is to determine RES penetration level that will not be curtailed with existing flexible powerplants in region. Additionally, impact of revitalization of existing and building of new hydropower plants on unconstrained penetration of RES will also be investigated. One way of balancing RES forecasting errors is also availability of external markets that can provide terms of flexible generation and regulating power to balance all the power systems. But if all neighboring power systems expect this kind of support regarding balancing issues its availability becomes very questionable. Therefore, this paper does not take into account adjacent electricity markets, in other words self-sufficiency of regional power systems is analyzed in the context of large RES penetration.

The rest of this paper is organized as follows: Section 2 describes the outline of the problem and methods used and while Section 3 presents the description of the model used for analysis. In this section, the optimization tool PLEXOS is also described. Section 4 presents used scenarios. Section 5 describes results obtained using CPLEX solver under the PLEXOS tool. The conclusion of this paper is presented in Section 6.

2 Problem description

As basis for this research and as main focus of this paper a model of regional power system has been made in PLEXOS software. Both model and software will be more discussed in next chapter of this paper.

Analysis provided within this paper can be divided in two main parts and each part has several scenarios that will be defined in Case Study chapter. The first part is focused on evaluation of penetration of signif-

ificant capacity of RES power plants considering current state of regional power system. Analyzed region consists of several countries from SE European region: Croatia, Serbia, Montenegro and Bosnia and Herzegovina. Goal is to estimate curtailment level for several RES penetration capacity scenarios and also associated curtailment distribution across region. Level of curtailment is calculated for both wind and PV power plants based on comparison between obtained results (from model in PLEXOS) and expected generation of each technology without constraints (excel calculation).

Following results and observations from first part of analysis second part of analysis is conducted. For the purpose of this part literature research was performed in order to identify PSH and HPP projects that are most likely to be executed in countries of interest. These planned assets are now added into existing model in appropriate nodes (countries). In this way system flexibility is boosted by these newly introduced power plants. It is important to note that other technologies (other RES, thermal power plants, nuclear power plants etc.) introduction is neglected on purpose in this paper in order to isolate effect of these technologies of interest. After insertion of new PSH and HPP and revitalization of existing PSH and HPP new levels of RES curtailment are estimated and compared to results from first part.

It is important to stress again that this paper does not take into account adjacent electricity markets effects for the reasons already stated in introduction part. Besides technical evaluation of HPP and PSH support to RES this paper does not provide additional economic feasibility of these projects.

Data for new HPP and PSH entries and also data for some scenarios regarding expected RES penetration by technology are taken from strategic national documents and other publicly available sources.

3 Model description

For the purpose of making model and running optimization a PLEXOS for Power Systems is used. It is product of Energy Exemplar very well-developed market simulation and optimization tool capable for different technical and economic analyses of power systems. It has already been widely used in researches and published papers [10], [15], [16], [17]. PLEXOS has been chosen as a tool for this paper based on previous author's experiences. Due to its large flexibility and available classes and settings PLEXOS can adapt to different power systems and market models, and it allows modeling of mixed hydro-thermoelectric power systems, which is especially important for the regional model of power systems of SE European countries (Croatia, Serbia, Montenegro and Bosnia and Herzegovina). PLEXOS is optimization/simulation tool based on object modelling which defines a hierarchical set of classes and user can easily choose and model the instances of needed objects.

Model is defined by input of required object parameters, scenarios, time horizons, time steps and other important modeling features and after model is finished PLEXOS runs mathematical optimization solver. Following solvers are available within PLEXOS: MOSEK, Gurobi, Xpress-MP and CPLEX. User also can choose which data is needed as output and PLEXOS provides user's interface for review and analysis of data in both table and graphical form.

Regional model of the power systems is created in the "PLEXOS for Power Systems" optimization tool. Model takes into account technical and economical parameters of generation units, availability, operating and maintenance schedules, future reinforcements and investments and electricity demand. Necessary data for model that were unavailable or not delivered following request of authors of this paper, were evaluated by the expert assessment.

Following characteristics are used for the purpose of modeling of a HPP and PSH:

- Number of generating units;
- Installed capacity of unit (MW);
- Pump load (MW)
- Pump efficiency (%)
- Minimum stable power level of each unit (MW);
- Efficiency curve that defines relation between water flow and power output;
- FO&M fee;
- VO&M fee;
- Rate of power increase in operating mode;
- Rate of power decrease in operating mode;
- Data regarding reservoir in case of reservoir HPP;
- Cascade formation model in case it is needed;
- Data regarding natural inflow and others.

The model of external electricity market model is not included due to already stated reasons.

Data regarding wind and PV power plants production in Croatia are available in hourly resolution. Same data for other countries are not available to authors. Either it lacks in terms of resolution or regional stamp. Therefore, expert judgement approach was used to extrapolate data from Croatian system to other neighboring systems. It has been done based on available data related to insolation and wind patterns for each county of interest.

Electricity load hourly pattern for each country has been taken from ENTSOe website for year 2017. Electricity load for each country is shown on next figures (Fig. 1 to Fig. 4.).

Figure 1: Electricity load for Croatia

Figure 2: Electricity load for Montenegro

Figure 3: Electricity load for Bosnia and Herzegovina

Figure 4: Electricity load for Serbia

The other power plants in modeled regional system (other RES, thermal, nuclear etc.) are modeled with same object in PLEXOS (Gerator) as HPP and PSH but with some additional necessary features:

- Fuel price;
- Fuel mix;
- Heat rate curve;
- Different start modes;
- Emission rate;
- Max and min time up;
- Max and min time down;
- Data regarding maintenance and others.

Power system of each country is modeled by one object (node within region) and four nodes are interconnected by several lines with certain power flow limit in both directions (Fig. 5.).

Simulation is conducted with the input parameters valid at the year 2017. Time horizon is one year (from Jan 1st, 2017 to Dec 31st, 2017) with the one-hour resolution and time step of one month. Although some papers suggest that RES power plant volatility balancing should be conducted by better time resolution (5 min or even 1 min) for the purpose of this paper time resolution is 1 hour. First reason for this is fact that main sources of power system flexibility are HPPs and PSHs that are very flexible in nature and can ramp up and down very fast. The other reason is model complexity, especially in terms of large number of modelled objects with associated numerous features, that requires significant execution time in case of time steps shorter than 1 hour. In most cases this prolonged execution time is not backed up by significantly different or better results.

Figure 5: Visualization of regional power system model in PLEXOS

4 Case study

As already mentioned, analyzed model in this paper considers power systems of several interconnected countries from SE Europe: Croatia, Serbia, Montenegro and Bosnia and Herzegovina. All existing power plants with available data are modeled with special attention on HPPs and PSHs. Total hydropower capacity in Croatia is around 2050 MW (of which 270 MW in PSH), in Serbia around 3510 MW (of which 615 MW in PHS), in Montenegro around 660 MW and in Bosnia and Herzegovina around 2115 MW (of which 215 MW in PSH). In short, modeled regional power system has installed total hydropower potential around 8330 MW of which 1100 in PSHs.

Table 1 Installed RES power capacity across region in Base scenario

RES technology	Wind [MW]	PV [MW]
Croatia	550	51
Serbia	21	15
Montenegro	26	0
Bosnia and Herzegovina	0	3

Table 2 Installed RES power capacity across region in 2030 scenario

RES technology	Wind [MW]	PV [MW]
Croatia	1050	210
Serbia	340	100
Montenegro	140	32
Bosnia and Herzegovina	160	25

Table 3 Installed RES power capacity across region in UNDP scenario

RES technology	Wind [MW]	PV [MW]
Croatia	6900	6900
Serbia	400	400
Montenegro	400	400
Bosnia and Herzegovina	2000	2000

First analyzed scenario is 'Base scenario' that takes into account already installed RES power capacity (Table 1). Based on this RES penetration across region modeled power system hydro flexibility is tested to estimate level of RES curtailment.

Base model and scenario is upgraded with RES installed capacity estimates for year 2030. [18-21]. This new scenario is called '2030 scenario'. Estimated installed RES power capacity is shown in Table 2.

Modeled power system hydro flexibility is again tested to estimate level of RES curtailment in this new scenario.

Next scenario, 'UNDP scenario' assumes that each country has installed maximum wind technical capacity [22]. PV installed capacity is assumed to be same as wind. Installed RES power capacities for this scenario are shown in Table 3. Modeled power system hydro flexibility is again tested to estimate level of RES curtailment in this new scenario.

Final stage of analysis is two step upgrade of UNDP scenario. In first step new planned HPP projects are taken into account and included into model. In this way model is extended by new 455 MW in Croatia, 270 MW in Serbia, 580 MW in Montenegro and 150 MW in Bosnia and Herzegovina [18-21] or 1455 MW in total. Modeled additional

power system hydro flexibility is again tested to estimate new level of RES curtailment in this new environment. In second step it is assumed that one new PSH (similar to PSH Bajina Bašta, 2 x 307 MW and reser-

voir of 190 GWh) is inserted into regional system. Its effects on RES curtailment in UNDP scenario are tested for several cases: A) new PSH inserted into Croatia; B) new PSH inserted into Serbia; C) new PSH inserted into Montenegro and D) new PSH inserted into Bosnia and Herzegovina. In this way it is also possible to estimate effects of positioning of new power plants that is of great importance due to fact that interconnection lines have certain limits.

Most of input data are taken from [23]. Results of presented scenarios are shown and discussed in next chapter.

5 Results and discussion

Results for scenarios Base scenario and 2030 scenario show that there is no curtailment at all regarding RES penetration level for both cases. In other words, there is enough flexibility and storage capacity in regional model to catch and allocate whole RES electricity production.

In Base scenario there was 1,25 TWh electricity produced yearly from wind power plants and additional 0,1 TWh electricity produced yearly from PV power plants that makes 1,35 TWh electricity from RES in total.

In 2030 scenario there was 3,66 TWh electricity produced yearly from wind power plants and additional 0,55 TWh electricity produced yearly from PV power plants that makes 4,21 TWh electricity from RES in total.

In UNDP scenario there are significant curtailment levels for both wind and PV power plants. Namely, out of totally available 20.055 TWh electricity in wind power plant, a total of 16.410 TWh was actually delivered in system. The rest is curtailed and results in 18,18% level of curtailment from wind power plants. On the other hand, out of totally available 14.265 TWh electricity in PV power plant, a total of 11.224 TWh was actually delivered in system. The rest is curtailed and results in 21,32% level of curtailment from wind power plants. Levels of RES curtailment for UNDP scenario by technology and country are shown in Fig. 6. From Fig. 6 it is obvious that most of the curtailment occurs in Croatia. It is due to fact that in UNDP scenario most of the RES capacity is also situated in Croatian power system. At the same time there is not enough load in Croatia to be covered by available RES sources and also there is not enough transmission capacity to evacuate that energy to surrounding systems. There is low level of curtailment also present in Bosnia and Herzegovina. It is also obvious that larger curtailment occurs for PV technology than in wind in both countries. In scope of this research it can be also concluded that keeping transmission lines same there is not enough storage capacity in terms of HPPs and especially PSHs, particularly in Croatia.

Figure 6: Levels of RES curtailment for UNDP scenario

It is interesting to realise that these levels of curtailment remains almost at the same levels even when new HPPs are introduced (mentioned in previous chapter). Reason for this is incapability of those power plants to consume and store electricity in periods with surplus of RES energy.

On the other hand, insertion of one new PSH similar to PSH Bajina Bašta can have great influence on level of curtailment, but this largely depends on location of insertion. If new PSH is inserted in Croatia total RES curtailment drops from 19,48% to 15,58%. If new PSH is inserted in Serbia or in Montenegro total RES curtailment remains same. If new PSH is inserted in Bosnia and Herzegovina total RES curtailment drops from 19,48% to 18,46%. These findings are in correlation to previous results. Therefore increase in storage

capability have larger effect if it is made in system with larger RES penetration level. In case of unconstrained interconnection between countries locational effects will be lost.

6 Conclusion

There is no doubt about crucial role of renewable energy source role in accomplishing goals of sustainable development. RES technologies are becoming economically competitive but besides financial support they need also strong research and technical support. This paper shows how important is to have adequate software tool and expertise in order to model and simulate power system phenomena, especially regarding RES aspects. Modeled power system is based on real regional system consisting of several countries from SE Europe: Croatia, Serbia, Montenegro and Bosnia and Herzegovina. This region has great potential in terms of RES utilization but at the moment that potential is not used in large share. Additional characteristic of modeled region is significant hydropower potential and installed hydropower capacity that is somewhere around 8,5 GW. This capacity consists of runoff river plants, plants with reservoirs and pumped storage plants. All of mentioned technologies can provide benefits to intermittent RES sources such as wind and solar and balance their volatile nature in order to keep system within certain limits. But in case of large RES penetration the most important role have PSH power plants due to their ability to act as load and energy storage. Therefore, PSHs can make transfer of electricity from periods with surplus of RES electricity to periods with low production levels from RES. In this way energy that would be otherwise curtailed can be stored and used later in same system. Paper also indicates that in interconnected systems very significant effects can be issued by interconnection lines constraints. It is therefore wise to examine optimal positioning of new PSH systems in order to utilize their potential at high levels. Having this in mind this paper concludes that same PSH will have different levels of benefit for regional system regarding country in which it is inserted. In this particular regional case Croatia has been shown to be the most suitable country to build new PSH capacities.

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