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OPTIMIZATION MODEL FOR VARIABLE RENEWABLE ENERGY SOURCES GENERATION: MACEDONIAN CASE STUDY

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Abstract: This paper is motivated by a large tendency of shift towards low emission electricity production, which can be achieved by substituting the conventional energy sources by renewable energy sources. Therefore, a share of renewable energy sources is continually growing. However, large-scale integration of renewable energy sources into the power system is a challenging task, since it depends on a balance between demand and supply at any time and because of the nature of renewable energy sources. The production from some sources such as the photovoltaic and wind power plants fluctuates depending on meteorological conditions, so it cannot be regulated. However, large hydropower plants can be regulated, so they are suitable for electricity balancing. In this paper, an optimization model is set for a system with 100 % renewable energy sources, which includes models for correlation of meteorological data and the production of electricity from different variable renewable energy sources. The resulting model gives an optimal ratio of production of variable renewable energy sources, which depends on the share of these sources in the total electricity production. The objective function of this optimization problem is to minimize the excess and lack of electricity production. For this purpose, hourly data for electricity consumption and hourly meteorological data are included. The results show that if only wind and photovoltaic power plants are considered, for the case of Macedonia, this optimum is found at 72% wind and 28% photovoltaic power production. However, if the already installed capacity of the big hydropower plants and the maximal potential of the small hydropower plants which make together 30% of the total installed capacity is taken into account, the optimal ratio of production from the other sources is: 50% wind power generation and 20% photovoltaic power generation.

Keywords: optimization model, renewable energy sources, Macedonian case study.

1. INTRODUCTION

There is an obvious trend of increasing renewable energy sources integration in the total electricity production. Key elements of future power systems are the variable renewable energy sources such as the wind and photovoltaic power plants [1]. A worldwide rise of the installed capacity of renewable energy sources is dramatic. For example, the installed capacity of wind power plants increased from 94 GW in 2007 to 283 GW in 2012 [2]. 100 GW of this installed capacity is located in the European Union [3]. The increase in the installed capacity of photovoltaic power plants is even greater. Globally, in 2007 the installed capacity was 10 GW, and by 2012 it increased 10 times and it is about 100 GW.

Therefore, modeling of the integration of variable renewable energy sources in the power system is of crucial importance. If the share of variable renewable energy in the system is not large, their variations can be absorbed into the system without consequences, but with an increase of their share, the stability of the system becomes more uncertain. In order for the integration of variable renewable energy sources in future systems with 100% renewable energy to be optimal, it is necessary to maximally exploit these sources, but with minimal needs for balancing the energy sources and minimal requirements for electricity storage [1].

Currently, there are three variable renewable energy sources in Macedonia: wind, solar and small hydro power plants. Therefore, in this paper we first

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made individual models for electricity production from these three sources, depending on the appropriate meteorological conditions. Then the optimization model has been applied to these models in order to get the minimum mismatch of electricity production and consumption. The optimal ratio depends to a large extent on the share of variable renewable energy sources in the total production.

The analysis of optimal ratio of electricity production from wind, sun and waves in the systems with large shares of variable renewable energy sources is made in [4]. In the paper the EnergyPLAN model is used which requires a big number of inputs, and is applied to the electric power system in Denmark. More practical and simpler model is presented in [5], which calculates the optimum electricity production only from photovoltaic and wind power plants. The model is applied to Europe as a whole. In [6] this model is extended to determine the necessary balancing and storage of electricity needs, because of the huge time difference between the electricity production and consumption from VRES. This model is also applied to the electric power system in Europe. In [7] this model is applied specifically to the electric power system in Denmark, and in [1] the model for the power grid is also included. The correlation between the integration of variable renewable energy sources, storage and balancing needs with the power grid is analyzed in [1], and so the model is applied to most of the countries in Europe.

In this paper the model described in [5] is used as a basis for the optimization model, which is supplemented to include the production from small hydropower plants and so an analysis of the optimal ratio depending on the total share of variable renewable energy sources in the total production is conducted. The model provides an opportunity for making a simple analysis and provides clear presentations of the guidelines and the limits of the development of 100% renewable energy sources-based power systems. For more specific and detailed analysis of some of the scenarios, a more precise model may be needed that will include more data, such as the cost of implementation of the same.

The paper is organized as follows. In chapter 2 a short overview of the current state of the electric power system of Macedonia is presented. The next chapter describes the individual electricity generation models for each of the three variable renewable energy sources analyzed: photovoltaic, wind and small hydro power plants. Appropriately, examples of their production, compared to the average consumption in Macedonia are given. In chapter 4 the generation optimization model is shown, which is applied to the Macedonian electric power system in the following chapter 5. Additionally, in this chapter the results provided by this model are presented along with an appropriate discussion. Finally, the conclusions are drawn in the last chapter of this paper, as well as the directions for future work.

2. ELECTRIC POWER SYSTEM OF THE REPUBLIC OF MACEDONIA

When it comes to electricity production in Macedonia, 64% of the installed generation capacity in 2014 depended on fossil fuels (mainly coal) [8]. Additionally, 36% of the installed capacity in 2014 was from renewable energy sources. This group includes large and small hydro, photovoltaic and wind power plants. There are 10 big hydropower plants with the total installed capacity of about 603 MW. The total capacity of small hydro power plants in 2014 was 59.5 MW, which is 3% of the total installed capacity. The installed capacity of photovoltaic power plants in 2014 was about 15 MW (1% of total capacity), and the installed capacity of the wind power plants was about 37 MW (about 2% of total capacity). However, a share of renewable energy sources is growing, which is also indicated by the following facts:

− The total installed capacity of small hydropower plants in Macedonia in 2014 is 0.61% higher compared to 2013.

− The total installed capacity of photovoltaic power plants in Macedonia in 2014 is 0.36% higher compared to 2013.

− The first wind power plant in Macedonia was built in 2014 (with installed capacity of 37 MW)

3. VARIABLE RENEWABLE ENERGY SOURCES MODELING

The variable renewable energy sources (VOIE) are a kind of renewable energy sources whose production cannot be controlled, because it only depends on meteorological conditions. Examples of VRES are the photovoltaic, wind and small hydropower plants. Unlike them, there are renewable energy sources that can be controlled to some extent such as for example, large hydropower plants with accumulation or the biomass power plants. Although the amount of available, for example, photovoltaic and wind energy may meet the annual needs of electricity consumption, the problem is that they are not available whenever they are needed.

3.1. Photovoltaic power generation modeling

The power production from photovoltaic power plants depends directly on the weather, that is, on the solar radiation on the analyzed location. Additionally, when analyzing the power production from photovoltaic power plants, the following assumptions for the characteristics of the electricity generator should be taken into account: angle of inclination, orientation and whether they are fixed or have an opportunity to follow the sun. The location that is analyzed is determined by its geographical coordinates. In order to calculate the hourly electricity production of this type of production facilities, it is necessary to calculate hourly solar radiation. In this paper, a combination of the Collares-Pereira and Rabl model [9] and the Liu-Jordan, Klein model [10-11] is used for hourly solar radiation calculation, which is explained in details in [12].

3.1.1. 100% photovoltaic power generation in Macedonia

If only photovoltaic power plants are used for electricity production, then that production should be compared with the electricity consumption. In order to achieve this, we set the total annual electricity production to be equal to the electricity consumption in a typical year. Although the annual electricity production is equivalent to the annual electricity consumption, the hourly and seasonal distribution of production and consumption differ a lot. Figure 1 shows the hourly electricity consumption for a typical year (which is calculated as the average consumption in four years (2010-2013) [13]), and hourly distribution of electricity production from photovoltaic power plants, when solar energy is the only source of electricity production. For these calculations, in the model for solar radiation, the data for Macedonia were entered [14]. It may be noted that in the summer there is much higher production than in the winter, which is opposite of the electricity consumption distribution. But, on the other hand, the production is carried out only during the day, when consumption is higher. Of course, there is no production during the night, but also, the consumption at night is much lower than during the day. Anyway, this scenario leads to a great need for balancing and storage of electricity.

3.2. Wind power generation modeling

The production of electricity from wind power plants also depends on meteorological data. In this case the distribution of electricity generation depends on the hourly wind speed. In order to make a correlation between the power generation and wind speed, it is necessary to use the production curves for the specific wind power plants.

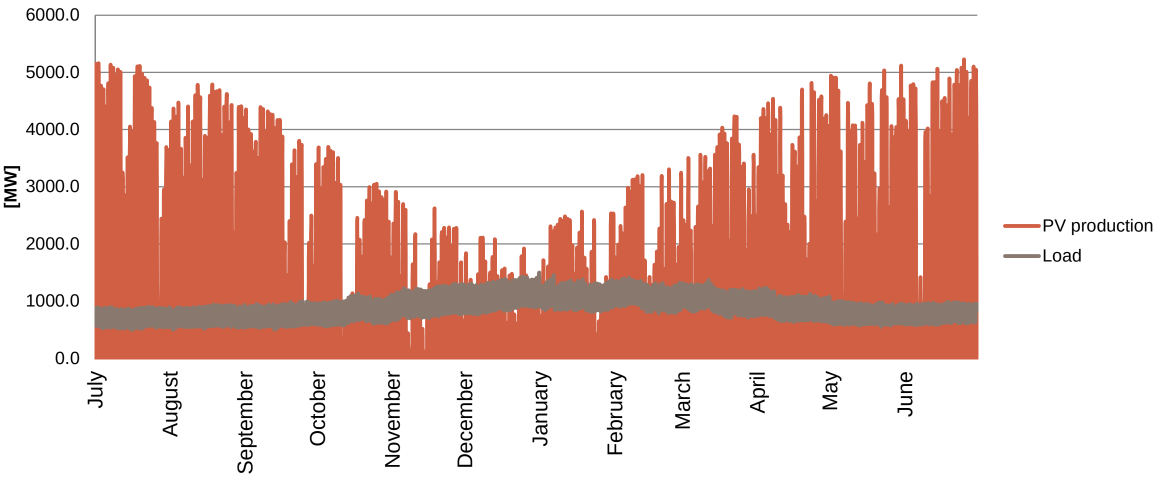

Figure 1. Hourly photovoltaic power production and consumption in a typical year in Macedonia

3.2.1. 100% wind power generation in Macedonia

The data for the production curves of the wind power plants are taken from [15], where there is information about wind power plants of four major manufacturers. This includes data for the kind of wind power plant that is currently installed in Macedonia, which is SIEMENS SWT-2.3MW-93m [16].

This scenario assumes that the only sources of electricity are the wind power plants. In this case, also, the annual output is equivalent to the consumption of electricity in a typical year. Figure 2 presents this scenario. It may be noted that the highest electricity generation from the wind power plants is in winter which coincides with the maximum power consumption. Additionally, the minimal electricity production and consumption are during the summer period. However, the variations of the electricity consumption are much smaller than the variations of the production. Furthermore, wind power generation is higher during the nights when the consumption is lower. Consequently, in this case also, there is a huge need for additional electricity generation and storage.

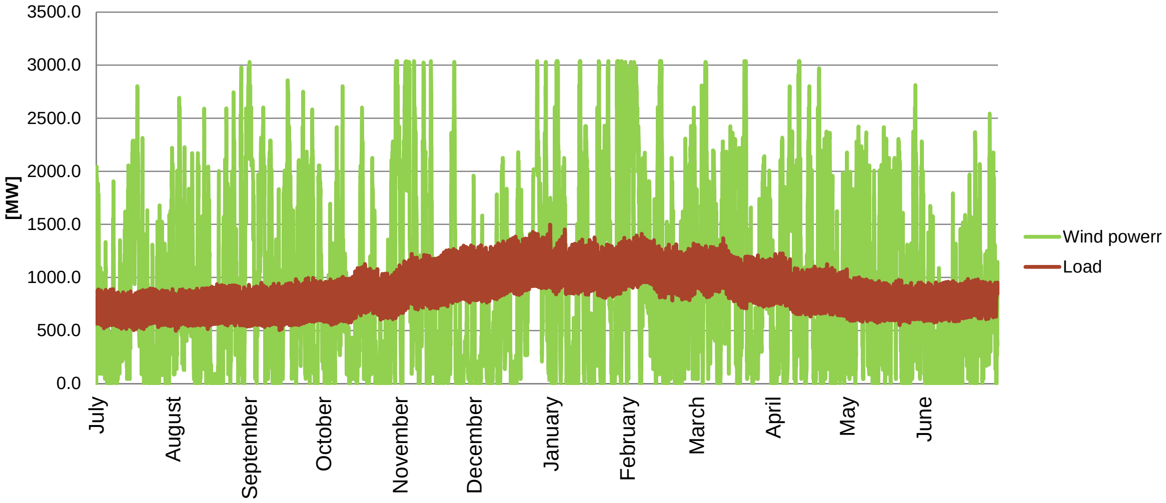

Figure 2. Hourly wind power production and consumption in a typical year in Macedonia

3.3. Modeling of small hydro power generation

Another type of electricity generators that depend on meteorological conditions is the small hydropower plants that have no possibility for water accumulation. Their production is directly dependent on the flow of water at a given time.

3.3.1. 100% small hydro power generation in Macedonia

The information about the flow of water on a monthly basis in Macedonia is taken from the dispatcher reports of MEPSO (Macedonian system operator) [17]. As an initial approximation, in this paper the distribution of the monthly flow of water at the hourly level is uniform. Figure 3 demonstrates the production of electricity from small hydropower plants, if they are the only source of electricity, and the electricity consumption in a typical year. Again, the annual production is equivalent to the annual consumption. It may be noted that the greatest production is in the spring period, when despite the flow of water from precipitation, there is also flow of water from melting snow. The lowest electricity generation is during the end of the summer period and the beginning of the autumn period.

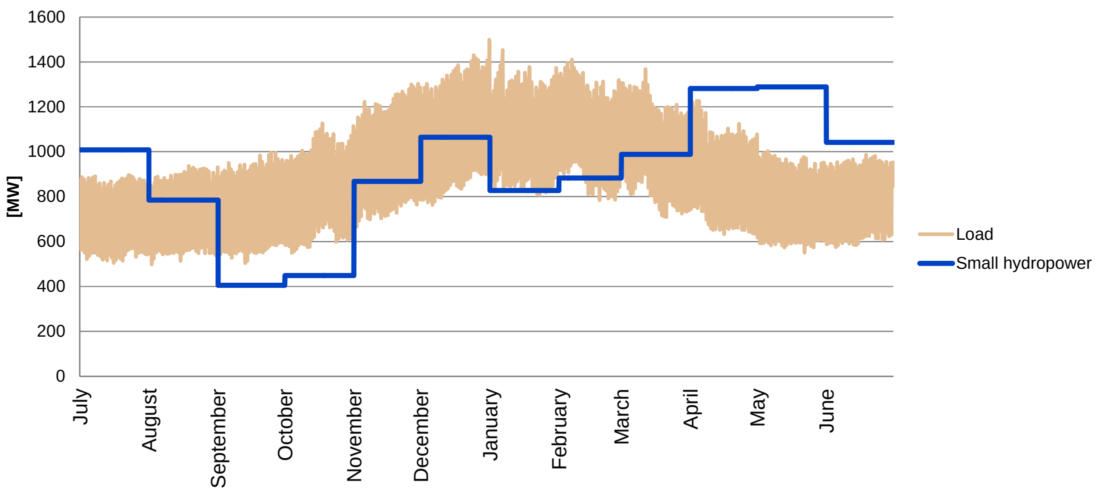

Figure 3. Hourly small hydro power production and consumption in a typical year in Macedonia

4. OPTIMIZATION MODEL

4.1. Generation-load missmatch

The main equation of the optimization model is equation (1) (which is based on the equations of the models given in [1] and [5−7]), where the difference or the imbalance of the production and the consumption is presented.

$$\Delta(t) = \left[a * w(t) + b * s(t) + c * h(t)\right] - l(t) \qquad (1)$$

In this equation, $w(t)$, $s(t)$ and $h(t)$ represent the power production at hour t from the wind, photovoltaic and the small hydro power plants, respectively. The electricity consumption at hour t is presented by $l(t)$.

The variable a shows a share of the electricity generation from the wind power plants from the overall electricity production. Similarly, b presents the fraction of the photovoltaic power production and the variable c presents the fraction of the small hydro power production.

There are three cases related to the difference between electricity production and consumption. The first case is when $\Delta(t)=0$, which means that the production is equal to the consumption of electricity at hour t. The second case is when $\Delta(t)>0$, which means that the production is higher than electricity consumption. In this case, there is an excess of electricity production which should be stored in the system. The last case is when $\Delta(t)<0$, or the generation is less than electricity demand. Then, the lack of production should be met by additional energy sources.

4.2. Optimization of the VRES power production

The model for optimization of the ratio of electricity generation from the variable renewable energy sources, depending on their share in the total electricity production is given by the equations (2) − (4).

The purpose of the model is to minimize the gap between production and consumption of electricity. Accordingly, the objective function in the model is given by the equation:

$$\min : \sum_t \left|\Delta(t)\right| \qquad (2)$$

This function is subject to few constraints, given by the following equations:

$$0 \le a \le a_{\max}, \quad 0 \le b \le b_{\max}, \quad 0 \le c \le c_{\max} \qquad (3)$$

where $a_{\max}$, $b_{\max}$, and $c_{\max}$are set to the corresponding maximal fraction of power generation from wind, photovoltaic and small hydro power plants.

Additionally, the following constraint should also be included in the model:

$$a + b + c = x \qquad (4)$$

where x is the fraction of the variable energy sources production in the overall electricity generation. This means that, if x=0,8, then 80% of the production is from variable renewable energy sources. The rest of the electricity generation may be covered by other renewable energy sources, whose production can be controlled to a certain extent, as the big hydro power plants or the biomass and biogas power plants. Of course, if we do not analyze the system with 100% renewable energy, coal or natural gas fired power plants may also be included. In this model, these technologies whose production can be controlled are modeled explicitly, because it is assumed that their hourly production corresponds to the consumption.

5. RESULTS AND DISCUSSION

The production from the wind and photovoltaic power plants has a large seasonal and daily dependence. For example, in the summer and during the day the production of the photovoltaic power plants is the highest. Unlike them, the production of the wind power plants is the highest in the winter period and during the night. Both of these energy sources are interesting in terms of modeling because they are able to balance each other to a certain extent. In order to minimize the need for balancing, the optimum production from these two sources should be found.

Firstly, a scenario where the only sources of energy are the photovoltaic and wind power plants is analyzed. Actually, it is assumed that there are no small hydro power plants and that the variable c is equal to zero and that the production of electricity is only from these two sources, that is $a + b = 1$. In that case, if we use the meteorological conditions of Macedonia, as well as the electricity consumption in Macedonia, the optimal production ratio is 72% of the wind power plants and 28% of photovoltaic power plants (Figure 4).

In this scenario, the total annual generation – load mismatch is high and amounts to 4943 GWh. Specifically, the positive difference is 2471 GWh, which is equal to the negative difference.

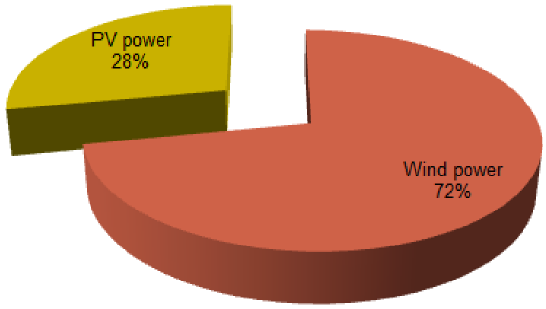

Figure 4. Optimal ratio of photovoltaic and wind power production in Macedonia

As currently in the electric power system of Macedonia there are small hydropower plants, logically, they should be included for electricity generation. The optimal ratio of production from wind, photovoltaic and small hydro plants depends on a share of the variable renewable energy sources in the total electricity production. Figure 5 shows the optimal ratio of these three energy sources depending on their share in the total production, which varies from 10% to 100%. It may be noted that the small hydropower plants have the highest share of variable renewable energy sources, because of their greater consistency, i.e. less variation in production compared to the production from photovoltaic and wind power plants. The share of production from photovoltaic power plants grows until the share of VRES achieves 50%, and then it begins to decline. On the other hand, the production from wind power plants is completely opposite. Actually, it is reducing until the share of VRES becomes 50%, and then it begins to rise. It is interesting that electricity generation from photovoltaic and wind power plants is balanced to a certain level, among the different cases. This conclusion is also presented in Figure 6 where the installed capacity of these three VRES is shown, depending on a share of VRES in the total production.

The excess and the lack of electricity generation depending on the share of VRES in the total electricity production are shown in Figure 7. The excess is equal to the lack of electricity generation, which is logical due to the fact that the total annual production equals total consumption. From Figure 7 it can be concluded that the excess, as well as the lack of electricity production is zero if the share of these renewable energy sources is less than 50%. With a share of more than 50%, the total surplus and lack of production increases, which should be covered by some other electricity generation source or, it should be stored in the system. It should be noted that the total excess and lack of production is calculated by multiplying $(1-x)$ by the sum of total consumption, which in fact represents the production from other energy sources.

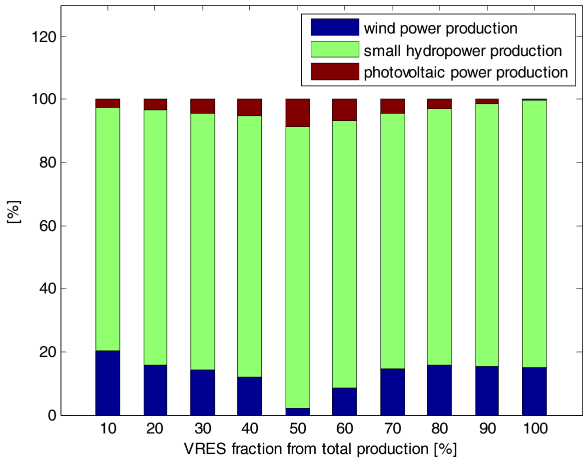

Figure 5. Optimal ratio of VRES depending on their share in total electricity production

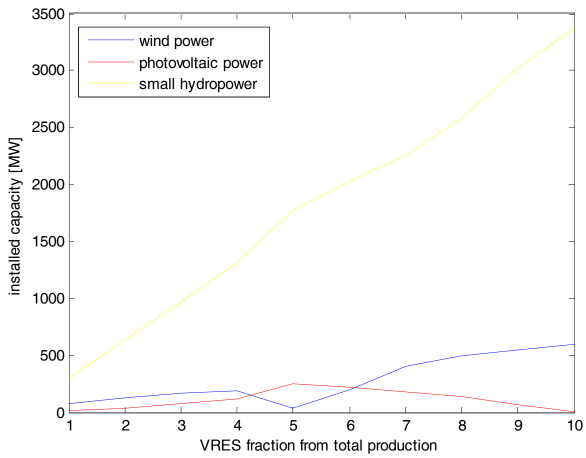

Figure 6. Installed capacity of VRES depending on a share of VRES in the total electricity production (where the share of 10 represents 100% VRES system)

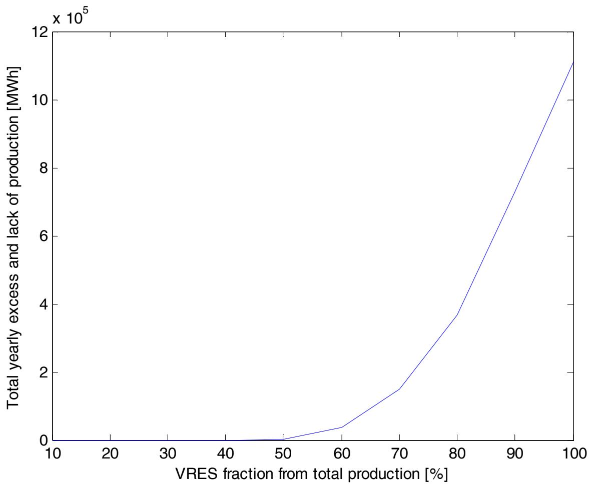

Figure 7. Total excess and lack of electricity generation depending on a share of VRES in the total production

Currently, the main renewable energy sources in Macedonia are the big hydro power plants that have accumulation. Their average annual production equals to about 20% of the average annual electricity consumption [13]. Therefore, it is logical to consider a scenario in which the share of variable renewable energy sources is 80% of the total production. In this case, the share of production from wind power plants is about 12% of total production, the share of photovoltaic power plants is about 3% and the biggest contribution is from small hydropower plants, which amounts to 65% (Figure 8). However, with this share of electricity production from small hydropower plants and their availability throughout the year it ensues that their required installed capacity is 2096 MW. According to [18] the maximum production from small hydropower plants is considered to be 10% of total electricity production. Therefore, if their production is limited, or c_{max} is set to be 0.1, the optimal production ratio from the other sources is: 50% wind power generation and 20% photovoltaic power generation (as shown in Figure 9). The total excess and lack of electricity generation in this case may be covered by a pumped hydro power plant, which in the cases of excess electricity production will pump the water into the reservoir or will act as a consumer, and in times of shortage it will generate electricity.

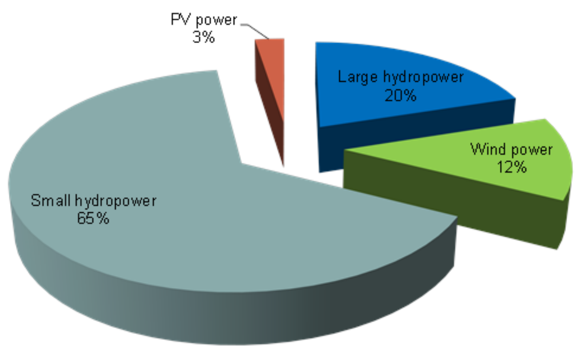

Figure 8. Share of VRES when the share of big hydropower plants is set to 20%

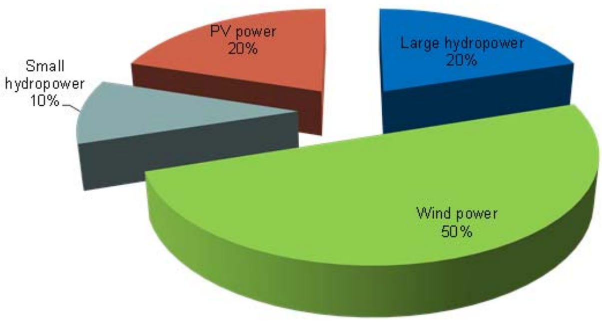

Figure 9. Share of VRES when the share of big hydropower plants is set to 20%, and the share of small hydropower plants is limited to 10%

6. CONCLUSION

In this paper an optimization model is defined which includes models for production of electricity from variable renewable energy sources that depend on meteorological data. As a case study, the Macedonian electric power system is analyzed. This model shows the optimal ratio of renewable energy sources in an electric power system. Additionally, by using this model the required installed capacity for electricity storage and balancing in each of the scenarios considered can be calculated, which could reduce the excess and the lack of electricity production to zero. In the current model, the power grid is not taken into account. Therefore, in the future, a model of the power grid may be incorporated in this model, so an analysis of how the network capacity impacts the integration of the variable renewable energy sources may be conducted.

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МОДЕЛ ОПТИМИЗАЦИЈЕ ЗА ПРОИЗВОДЊУ ИЗ РАЗНИХ ИЗВОРА ОБНОВЉИВЕ ЕНЕРГИЈЕ: СТУДИЈА СЛУЧАЈА МАКЕДОНИЈЕ

Сажетак: Овај рад је мотивисан великом тенденцијом прелаза на производњу електричне енергије уз смањену емисију штетних гасова, која се може постићи замјеном извора конвенционалне енергије са обновљивим изворима енергије. Стога удио извора обновљиве енергије константно расте. Међутим, масовнија интеграција обновљивих извора енергије у електро систем је изазован задатак, будући да зависи од равнотеже између потражње и понуде у било ком тренутку због природе обновљивих извора енергије. Производња из неких извора као што су фотонапонске и вјетроелектране варира у зависности од метеоролошких услова, тако да ју је немогуће регулисати. Међутим, велике хидроелектране се могу регулисати, па су погодне за балансирање електричне енергије. У овом раду постављен је модел оптимизације за систем са 100%-тним обновљивим изворима енергије, који укључује моделе за корелацију метеоролошких података и производњу електричне енергије из различитих варијабилних извора енергије. Модел који се добије даје оптималан однос производње из варијабилних обновљивих извора енергије, што зависи од удјела ових извора у укупној производњи електричне енергије. Циљна функција овог модела оптимизације је да се на минимум сведе вишак као и мањак производње електричне енергије. У ту сврху, дати су подаци о потрошњи електричне енергије и метеоролошки подаци, из сата у сат. Резултати показују да ако се разматрају само вјетроелектране и фотонапонске електране, у случају Македоније, тај оптимум се налази на 72% за производњу у вјетроелектранама и 38% за производњу у фотонапонским електранама. Међутим, ако се узме у обзир већ инсталирани капацитет великих хидроелектрана и максималан потенцијал малих хидроелектрана које заједно чине 30% укупно инсталираних капацитета, оптимални однос производње из осталих извора је: 50% производња из вјетроелектрана и 20% производња у фотонапонским постројењима.

Кључне ријечи: модел оптимизације, обновљиви извори енергије, Македонска студија случаја.

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