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IMPACT OF PHOTOVOLTAIC POWER PLANTS ON THE OVERALL ELECTRIC POWER SYSTEM OF THE REPUBLIC OF MACEDONIA

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Abstract: In this paper we analyze the impact of the renewable energy sources on the overall electric power system of the Republic of Macedonia. Specifically, the effect of the photovoltaic power plants is examined. For this purpose we developed an electricity production optimization model, based on standard network flow model. The renewable energy sources are included in the model of Macedonia based on hourly meteorological data. Electricity producers that exist in 2012 are included in the base scenario. Two more characteristic years are analyzed, i.e. 2015 and 2020. The electricity producers planned to be constructed in these two years (which include the renewable energy sources) are also included. The results show that the renewable energy sources introduce imbalance in the system when the minimum electricity production is higher than the electricity required by the consumers. But, in these critical situations the production from photovoltaic energy sources is zero, which means that they produce electricity during the peak load, and do not produce when the consumption is at minimum.

Keywords: power plant, electric power system, electricity consumption and transmission, photovoltaic power plant.

1. INTRODUCTION

There is an obvious trend to increase the inclusion of renewable energy in the total electricity production. The worldwide growth of installed capacity of renewable energy is dramatic. For example, the installed capacity of wind power increased from 94 GW in 2007 to 283 GW in 2012 worldwide [1]. Of this, 100 GW of installed capacity is in the European Union [2]. An increase in the installed capacity of photovoltaic power plants is even higher. Worldwide, the installed capacity was 10 GW in 2007, and by 2012 it increased 10 times, i.e. it was about 100 GW.

In 2012 the total installed capacity of renewable energy sources in Macedonia is around 40 MW, which is about 2 % of total installed capacity [3]. Until 2012, two types of renewable energy sources for electricity production are present in the electric power system in Macedonia: photovoltaic power plants (with the installed capacity of 3.8 MW) and small hydro power plants (with the installed capacity of 36 MW). The 10th Energy Community Ministerial Council agreed on the implementation of EU Directive 2009/28/EC on the promotion of renewable energy (RES Directive) by the Energy Community, which specified a target share for renewable energy for Macedonia in 2020 at the level of 28 % [4].

Because of the upward trend of construction of new renewable energy sources, both in the world and in Macedonia, in this paper we analyze how the overall power system will be affected by this. The main problem of renewable energy sources is that they do not produce electricity permanently, i.e. their production is variable and to some extent unpredictable [2]. Their production depends on weather conditions and according to the European (and the Macedonian) legislation they must be included in the system as they produce electricity. Therefore, renewable energy sources highly affect both the level of system backup of installed capacity, the rate at which these reserves should be developed [2,5] and the regulation of the other energy sources covering the base load and the peak load. This analysis is pursued in [2,5].

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In this paper we investigate the impact of the renewable energy sources on other energy sources and the stability of the overall system in Macedonia. For this purpose we used a linear programming model for optimization of energy production. In fact, the goal was to make optimization that would meet the electricity demand at the lowest cost in each hour, while taking into account the given constraints. Thus, the result shows the power at which each of the power plants should run most economically to meet the demand in that hour. Electricity production cost of each source of electrical energy depends on the cost of fuel, the cost of operation and maintenance.

Similar models are used for various analyses of the electric power systems. The objective function can include many other parameters, according to which the optimization is made, depending on the performed analysis. For example, [2] and [6] include start-up costs of each of the power generators. In this paper, we determine the availability of the power plants on annual level, and repairing of the thermal and CHP plants is performed in predetermined periods. The authors in [7] take into account the environmental pollution. An optimization model is used to analyze the Lebanon power system and to optimize the production of each power source taking into account the minimum cost and pollution in [7]. In [8] optimization of the electricity generation mix is incorporated with the life cycle external costs, which includes the evaluation of the corresponding environmental impact. This model is applied to the case of Greece. In [9] an hour-by-hour optimization model is used in order to plan the power generation and capacity mixes to meet future electricity demand. This model is applied to the case study of Tokyo, Japan.

The paper is organized as follows: in the following chapter we give a review of the structure of the electric power system of the Republic of Macedonia; then we present the electricity production optimization model. The next chapter describes the modeling of the electric power system of Macedonia. In the following chapter we present the results, the corresponding analyses and the discussion of the results. Finally, the last chapter concludes the paper.

2. ELECTRIC POWER SYSTEM OF THE REPUBLIC OF MACEDONIA

In this chapter we give an outline of the installed capacity of each type of electricity producers that exist in Macedonia until the end of 2012. Electricity in Macedonia is mainly generated in two lignite-fired thermal power plants: Bitola and Oslomej. There are also three combined heat and power plants: CHP Skopje, CHP Energetika and CHP Kogel. They generate electricity and heat from natural gas. There is also one heavy fuel oil fired thermal power plant - Negotino.

Table 1 gives an overview of the basic parameters of the thermal power plants, such as the installed capacity and the fuel type used for producing electricity.

Table 1. Installed capacity and fuel type of thermal power plants in Macedonia [3]

Power plant	Installed capacity [MW]	Fuel type
TE Bitola	675	Lignite
TE Oslomej	125	Lignite
TE Negotino	210	Heavy fuel oil
CHP Energetika	30	Natural gas
CHP Kogel	30	Natural gas
CHP Skopje	227	Natural gas

There are 10 big hydro power plants in Macedonia, with 603 MW of total installed power. The total capacity of small hydro power plants in 2012 is 35,62 MW, which is 1.88% of total installed capacity.

The total installed capacity of photovoltaic power plants by the end of 2012 is 3,787 MW.

3. ELECTRICITY PRODUCTION OPTIMIZATION MODEL

The electric power system is presented as a network of *n* nodes, interconnected by lines. The nodes represent the electricity producers and electricity consumers. In order to represent the problem as a standard network flow model the generation nodes are transformed. Transformation is used in order to associate cost and capacity to each generator. This is done by replacing each of the generation nodes with a pair of nodes with an edge connecting them [10] and [11]. This edge is characterized by generator parameters, such as generation cost, maximum and minimum electricity production.

The goal is to model the electric power system as a linear programming problem whose objective function is to minimize the total production cost (Equation (1)).

$$\min : \sum_{i=1}^{k} c_i g_i \tag{1}$$

where c_i is the generation cost of each power plant and g_i is the power produced by generator i, measured in MW. The cost of electricity production of each type of power plant depends on the cost of fuel, and on the operating and investment cost. The generators are represented by the first k nodes, and electricity consumers and transshipment nodes are represented by the nodes $k+1$ to n.

The total power produced should be equal to the total power consumed and the total power loss, at each given moment. If we include the power losses during transmission in the total power consumption, the balance in the system is expressed by the equation:

$$\sum_{i=k+1}^{n} (d_i) + \sum_{i=1}^{k} (-g_i) = 0 \tag{2}$$

where the first summation represents the total power consumption and the total power losses through the electricity transmission.

The linear programming problem is subject to constraints. One of the constraints is given by the equation (3).

$$p = A \cdot \begin{bmatrix} -g \\ d \end{bmatrix} \tag{3}$$

where p is a vector whose components are the power flows through the lines, g is a vector representing power produced by the generators, d is a vector containing the quantity of power required and A is a node-incidence matrix. Another constraint that should be included is given in the equation:

$$P^{\min} \le |p| \le P^{\max} \tag{4}$$

where P^{max} and P^{min} are vectors containing the maximum and the minimum power flows through the lines. For the first k lines this constraint corresponds to the maximum and minimum power available from the generators, and the remaining lines are constraints of the transmission lines.

4. MODELING OF THE ELECTRIC POWER SYSTEM OF MACEDONIA

To analyze the electric power system in Macedonia the optimization is done on an hourly basis. This means that for a period of one year, optimization is done for each hour in the year, taking into account the electricity consumption and the available electricity generation in that hour.

Electricity generators

We have included the electricity generators that exist in Macedonia: lignite thermal power plants, combined heat and power plants, hydro power plants and renewable energy sources.

For each thermal power plant the information for the installed capacity is included. For technical reasons the lignite thermal power plants and one of the combined heat and power plants (with the installed capacity of 227 MW) cannot operate under certain minimum production, which is about 70% of the installed capacity nor can they be turned off on a daily basis. So the information about the minimum and maximum available production during the year should be included. This also implies the availability of the power plant, which corresponds to its modernization or repairing during a certain period of the year, when the minimum and the maximum production is equal to zero.

Hydropower plants are mainly used for peak electricity load and to balance the electricity production and consumption. This is because they can easily be turned on and off, or their minimum production is zero.

Electricity import is also modeled as electricity production and is represented by two production nodes. The first one corresponds to the previously agreed import that has a lower price and the other node corresponds to import during peak electricity consumption, when its price is higher.

Renewable energy sources

Renewable energy sources are included in the system as electricity generators with the lowest generation prices (which correspond to the feed-in tariffs). According to the Macedonian (as well as the European) regulations, they have to be included in the system when they produce electricity which depends on the meteorological conditions. This is achieved by setting the electricity generation prices from these sources equal to zero, so that they have absolute advantage in each moment. We have considered the photovoltaic, small hydro and wind power plants.

For photovoltaic power plant modeling, hourly meteorological data for cloudiness during the year are used. To calculate the cloudiness for each hour, the meteorological data for Macedonia are used, for two characteristic years. The data were in the range [0-8], where the value 8 means the highest cloud coverage. We have scaled this data in the range [0-1], so that the value 1 means that there are no clouds. An average value is calculated for two years.

Furthermore, the average time of sunrise and sunset is calculated for each month, i.e. [12] and [13], so that when there is no sun, photovoltaic power plants do not produce electricity. As an approximation during the day, about noon time the electricity production is the highest and is calculated by multiplying the installed capacity by cloudiness (which is in the range [0-1]). During the remaining time in a day this product is multiplied by a certain coefficient (which is less than 1). In this way the maximum yearly production by photovoltaic power plants is preserved, which is for Macedonia equal to 1400 hours multiplied by the installed capacity.

The production of small hydro power plants which do not have accumulation is also modeled taking into account the meteorological data. The production is proportional to the cloudiness and the rain intensity. Furthermore, there is also production in spring time when it is sunny, which corresponds to the snow melting.

For the wind power plants the meteorological data for the wind intensity are used. Accordingly, the electricity production in the wind power plants is proportional to the wind intensity, preserving the maximum availability of the wind power plants.

Electricity consumption

Electricity consumption is represented by nine nodes corresponding to the biggest cities in Macedonia and one node that corresponds to the biggest industrial consumption. Consumption is distributed among the cities according to the population.

Export is also modeled as an electricity consumer. Export can be previously agreed or otherwise used when the minimal electricity production is higher that the electricity consumption. In these situations there are two solutions. The first one is to turn off one of the thermal power plants which is very expensive and is not done on a daily basis. Another option is to export excess electricity produced to the regional electric power system, which is bigger and can accept these relatively small excesses of electricity. The latter case is modeled so that the consumption of the export node is equal to the difference between the total minimum electricity production and the total electricity consumption.

Electricity transmission

Network structure of the electric transmission system is not considered in this paper and each electricity producer is connected to each electricity consumer. These lines have sufficiently high capacity so that the flow is practically not constrained. The lower bound is equal to zero. The losses in the power transmission system are included in the electricity production.

5. RESULTS AND DISCUSSION

In this paper we have analyzed three characteristic years: 2012, 2015 and 2020.

For 2012 all the available electricity generators presented in the section – “ELECTRIC POWER SYSTEM OF THE REPUBLIC OF MACEDONIA” are used. For the availability of the power plants, for TPP REK Bitola it is assumed that each of the three blocks is being repaired during about 40 days in different periods of the year. This means that one block is turned off from 15th March to 15th April, June, July and September. TPP Oslomej is turned off during three months in the year (March, June and July). The installed capacity of the renewable energy sources is given in Table 2.

Table 2. Installed capacity of renewable energy sources for three analyzed years [14]

	2012	2015	2020
Wind power plants	/	36 MW	100 MW
Small hydro power plants	36 MW	80 MW	130 MW
Photovoltaic power plants	3.8 MW	10 MW	25 MW

In 2015 one hydro power plant is added with installed capacity of 36 MW [15]. For TPP REK Bitola it is assumed that each block is being repaired during one month in a year (June, July and August). TPP Oslomej is turned off during two months and CHP power plants are turned off in the summer (15th April to 15th October). The installed capacity of the renewable energy sources in 2015 is given in Table 2.

In 2020 we have added two more hydropower plants with 126 MW of installed capacity and two combined heat and power plants with 60 MW of installed capacity [15]. The availability of the power plants is the same as in 2015, only the combined heat and power plants are turned off during one month only (May). The installed capacity of the renewable energy sources is given in Table 2.

Table 3 shows the prices for electricity generation that are used in the model the three analyzed years. In 2012 the price of natural gas was very high and is expected to become lower in the future. Basically, Table 3 shows the ratio between the prices of different electricity generators.

The data for the total hourly electricity consumption including the power losses for 2012 are used [19]. The total electricity consumption is assumed to be 9100 GWh and 10500 GWh in 2015 and 2020, respectively [15]. This consumption is distributed hourly proportionally to the data from 2012.

Table 3. Ratio of the electricity generation prices [16−18]

	2012	2015	2020
Hydro power plant	60	60	60
Lignite fired thermal power plant	40	40	40
Combined heat and power plant	110	60	60
Heavy fuel oil fired power plant	120	120	120
Previously agreed import	40	40	40
Peak load import	70	70	70

Using the input data described above, Figure 1 shows the electricity production share for 2012. Most electricity is produced by the lignite-fired thermal power plants. Import is very high in this year, because the production from the combined heat and power plants is very low due to the high price of natural gas. A share of renewable energy sources in the electricity production is less than 2%, of which about 0.05% from the photovoltaic power plant. Figure 2 shows the renewable energy sources production in the year 2012.

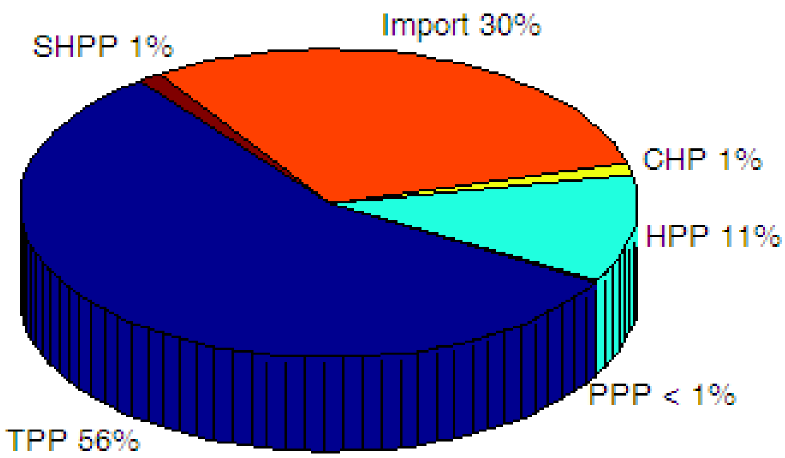

Figure 1. Electricity production share for 2012

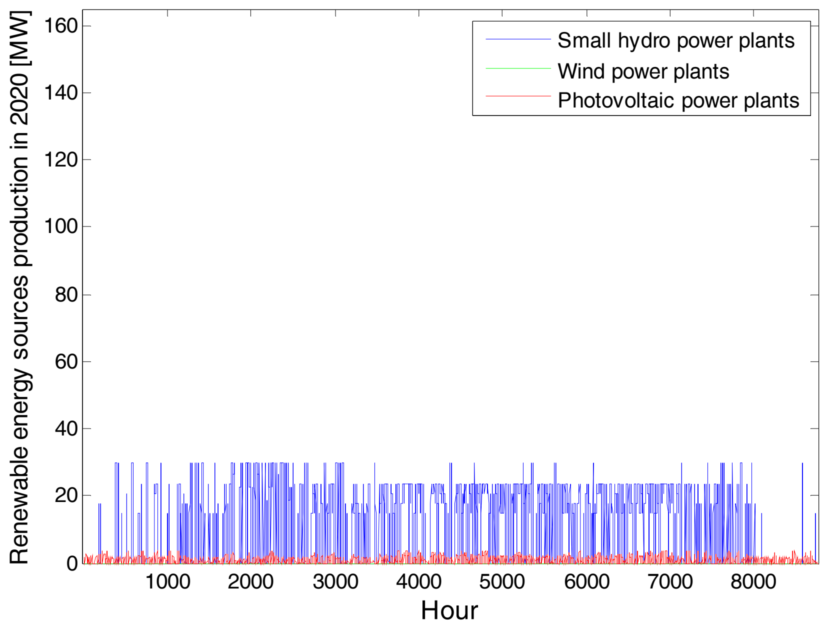

Figure 2. Renewable energy sources production in 2012

Figure 3 and Figure 4 show the situations in 2015 and 2020, accordingly. It is obvious that import has decreased, mainly because of lower price of natural gas and installing of new generation capacities. Among the new installed capacities are also the renewable energy sources (as shown in *Table 2. Installed capacity of renewable energy sources for three analyzed years)*. Consequently, the renewable energy sources production share is increased to about 3% in 2015 and about 5.3% in 2020. Specifically, the production from photovoltaic energy sources is increased to 0.15% in 2015 and 0.33% in 2020. An absolute increase in the renewable energy sources production can easily be seen in Figure 5 and Figure 6 where the production of these producers is presented for two years.

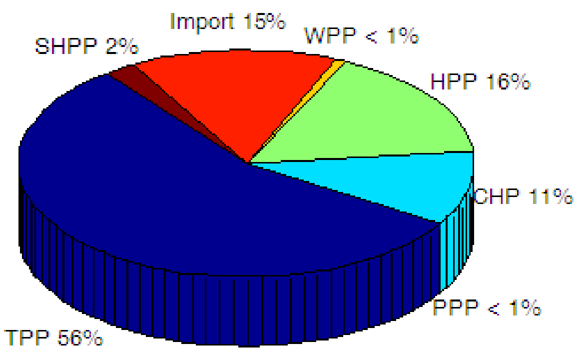

Figure 3. Electricity production share for 2015

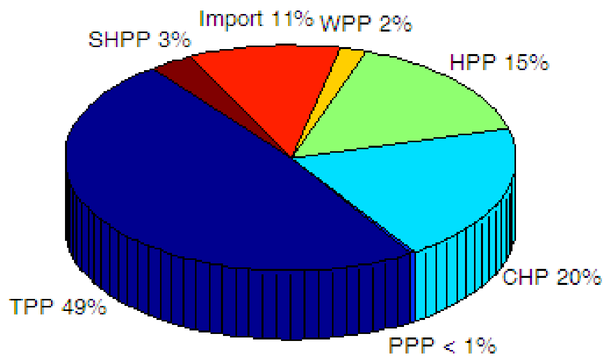

Figure 4. Electricity production share for 2020

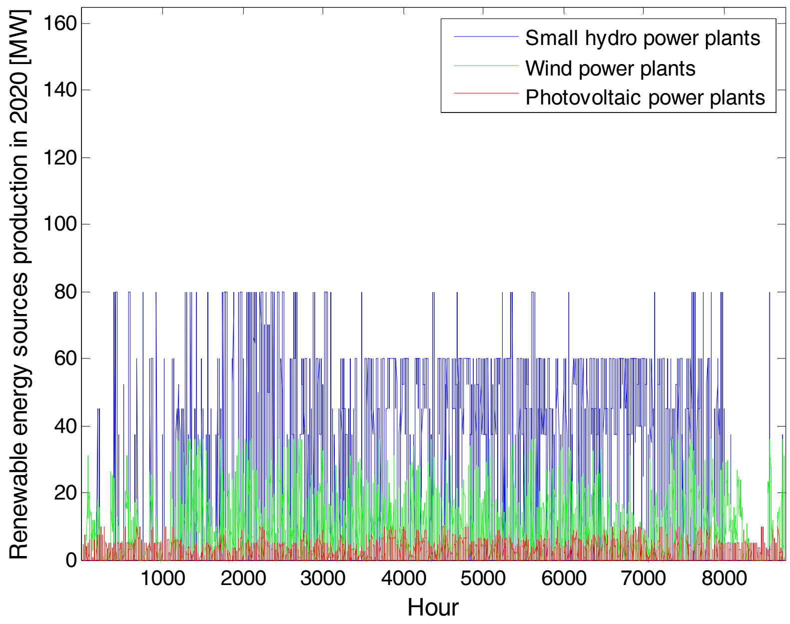

Figure 5. Renewable energy sources production in 2015

There are situations when the minimum production is higher than the total consumption. This happens when the consumption is very low, for example during the nights and the production of the thermal power plants is at minimum and there may be production from the renewable energy sources which according to the regulations have to be included in the system. In these situations there is a problem with the balance of the system so that the excess of electricity production has to be exported to the regional electric power systems.

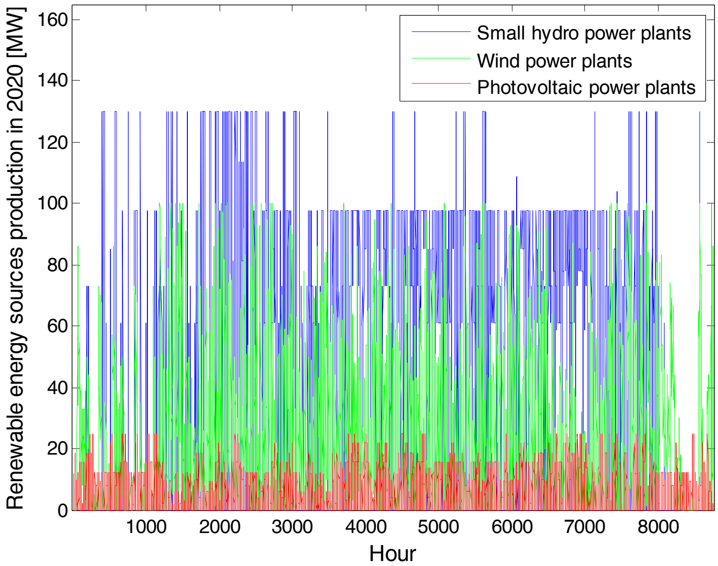

Figure 6. Renewable energy sources production in 2015

Figure 7, Figure 8 and Figure 9 represent the electricity load (green line), the minimum electricity production which includes the renewable energy sources (red line) and the excess of electricity production or the export (blue dots) for each hour of three analyzed years, i.e. 2012, 2015 and 2020, respectively. Critical situations occur when the green line i.e. the electricity load is below the red line or the minimum production. This red line represents the minimum installed capacity of thermal power plants which are base electricity producers and cannot be turned off on a daily basis, and the renewable energy sources. Specifically, Figure 10, Figure 11 and Figure 12 show which of the renewable energy sources produce electricity in these hours. As it can be seen, most electricity is produced by small hydro power plants and the rest is produced by the wind power plants, while there is no production by the photovoltaic power plants.

It can be concluded that photovoltaic electricity generators do not produce electricity in these critical situations when electricity consumption is very low. Consequently, they do not introduce imbalance in the system as the other renewable energy sources. This conclusion can be explained by the fact that photovoltaic power plants do not produce electricity when the power consumption is very low which is mainly during nights.

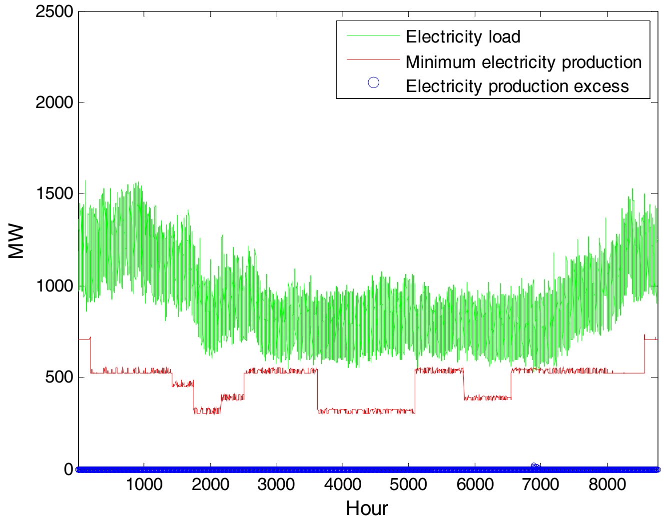

Figure 7. Electricity load, minimum electricity production (which includes the renewable energy sources) and the excess of electricity production in 2012

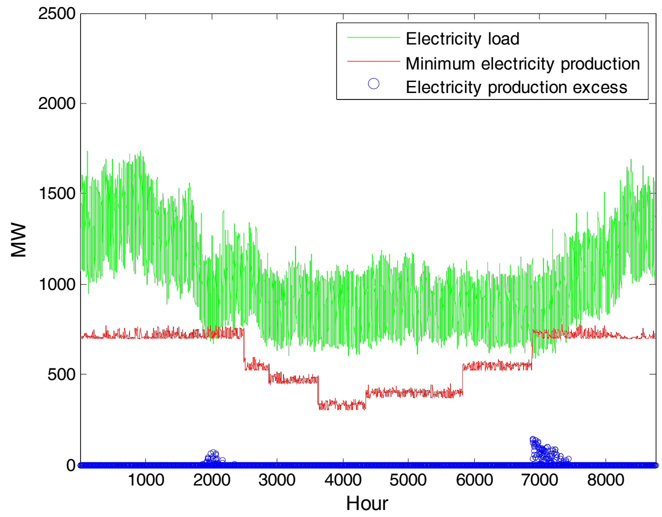

Figure 8. Electricity load, minimum electricity production (which includes the renewable energy sources) and the excess of electricity production in 2015

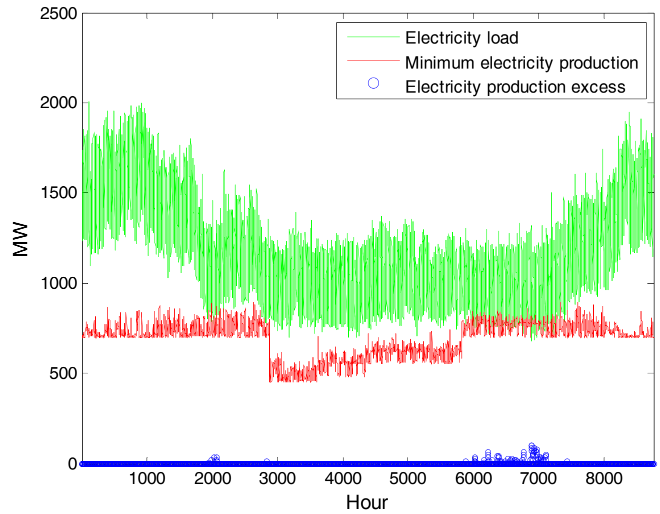

Figure 9. Electricity load, minimum electricity production (which includes the renewable energy sources) and the excess of electricity production in 2020

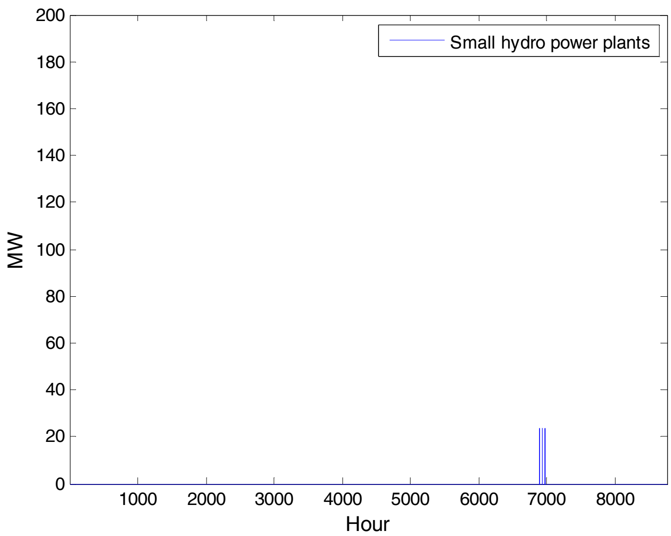

Figure 10. Renewable energy sources production in the situations of excess electricity production in 2012

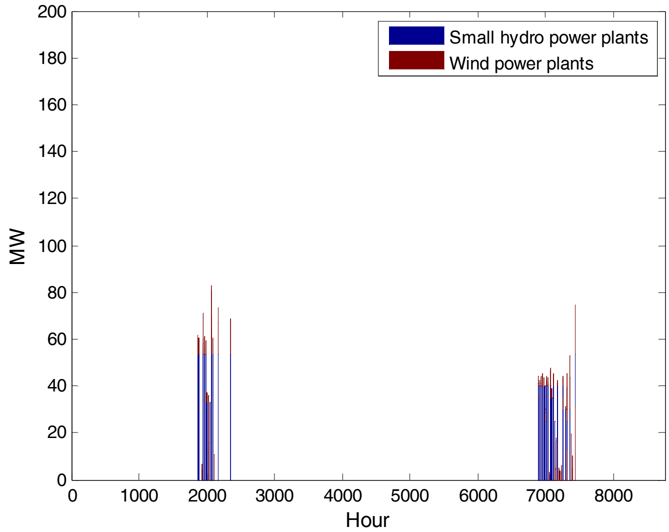

Figure 11. Renewable energy sources production in the situations of excess electricity production in 2015

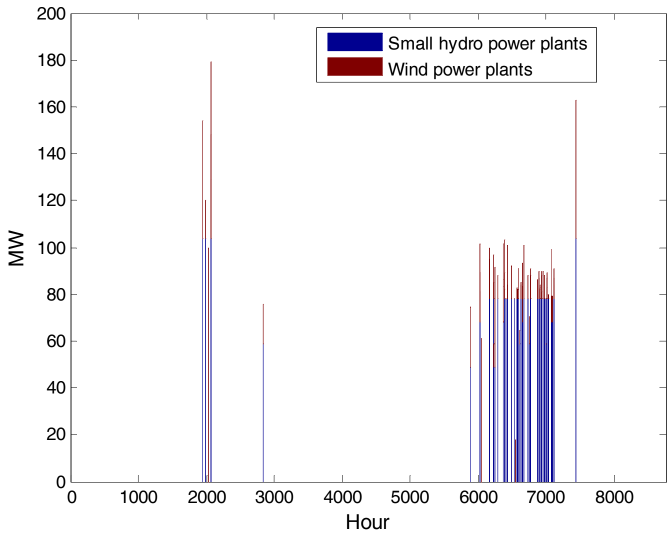

Figure 12. Renewable energy sources production in the situations of excess electricity production in 2020

6. CONCLUSION

In this paper we have analyzed the electric power system of Macedonia for three years: 2012, 2015 and 2020. We have increased the installed capacity of renewable energy sources according to "Strategy for Utilization of the Renewable Energy Sources in the Republic of Macedonia by 2020" [14]. The results show that the renewable energy sources introduce imbalance in the system when the minimum electricity production is higher than the electricity required by the consumers, and according to the European legislation, renewable energy sources have to be included in the system if they produce electricity. But, it is interesting that in these critical situations the production from photovoltaic energy sources is zero. This is because the critical situations mainly occur at nights, when the photovoltaic power plants do not produce electricity. Consequently, the photovoltaic power plants did not introduce instability in the system, although we have increased the installed capacity from 3.8 MW in 2012 to 25 MW in 2020.

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УТИЦАЈ ФОТОНАПОНСКИХ ЕЛЕКТРАНА НА ЦЈЕЛОКУПНИ ЕЛЕКТРОЕНЕРГЕТСКИ СИСТЕМ У РЕПУБЛИЦИ МАКЕДОНИЈИ

Сажетак: У овом раду анализира се утицај обновљивих извора енергије на цјелокупни електроенергетски систем у Републици Македонији. Нарочито се истражује ефект фотонапонских електрана. У ту сврху развијен је модел оптимизације производње електричне енергије, заснован на стандардном моделу тока мреже. Обновљиви извори енергије уврштени су у македонски модел на основу метеоролошких података из сата у сат. У основни сценарио укључени су произвођачи електричне енергије који постоје у 2012. години. Анализиране су још двије карактеристичне године, 2015. и 2020. У овим годинама узети су у обзир произвођачи електричне енергије (који укључују и обновљиве изворе енергије) чија се изградња планира. Резултати показују да обновљиви извори енергије уводе неравнотежу у систем када је минимална производња енергије виша од електричне енергије која је потребна потрошачима. Али, у овим критичним ситуацијама производња из фотонапонских извора енергије је на нули, што значи да они производе електричну енергију при вршном оптерећењу а не производе када је потрошња на минимуму.

Кључне ријечи: електрична централа, електроенергетски систем, потрошња и пренос електричне енергије, фотонапонска електрана.