TECHNICAL UNIVERSITY OF GABROVO

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ANALYSIS OF THE OPPORTUNITIES FOR IMPLEMENTATION OF NEW PHOTOVOLTAIC POWER PLANTS IN THE ELECTRICAL ENERGY SYSTEM IN THE REPUBLIC OF NORTH MACEDONIA

A B S T R A C T

of a dissertation work for awarding an
educational and scientific degree PhD

Field of higher education:	5. Technical sciences
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The dissertation was discussed and directed for official defense at a meeting of the Extended Departmental Council of the Department of "Electric Power Distribution and Electrical Equipment" at the Faculty of "Electrical Engineering and Electronics" of the Technical University - Gabrovo, held on 24.01.2024.

The dissertation contains 172 pages. The scientific content is presented in an introduction, five chapters and a conclusion, includes: 100 figures and 29 tables. 96 literary sources and 43 Internet addresses are cited. The numbering of figures, tables and formulas in the abstract is consistent with that in the dissertation.

The research on the dissertation work was carried out in the Department of "Electrical Supply and Electrical Equipment" at the Faculty of "Electrical Engineering and Electronics" of the Technical University - Gabrovo and on the territory of the city of Gabrovo.

The official defense of the dissertation work will take place on April 26, 2024 at 1:00 p.m. in room 2603, building Academic Building 2A (Bajdar) of the Technical University - Gabrovo.

Defense materials are available for those interested in room 3209, building №3 Rectorate of the Technical University - Gabrovo.

The reviews and opinions of the members of the scientific commission and the abstract are published on the university's website: www.tugab.bg.

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I. GENERAL CHARACTERISTICS OF THE DISSERTATION

Actuality of the problem:

In recent years, the traditional production of electricity from conventional energy sources has been the largest source of industrial air pollution. Air quality deterioration, global warming data, as well as periodic local energy crises require a transition to new primary energy sources that do not pollute the environment and provide additional opportunities to increase energy independence.

The subject of research in the dissertation is the photovoltaic power plants and their commissioning, as new capacities in the electricity system of the Republic of North Macedonia, to replace the old non-ecological and polluting power plants with harmful emissions.

Purpose and tasks of the dissertation:

The main goal of the dissertation is to analyze the opportunities for implementation of new photovoltaic power plants in the electricity system of the Republic of North Macedonia. In order to achieve the main goal, it is necessary to complete the following tasks:

1. To study good practices from the neighboring countries of the region and analyze the energy balance during the implementation of renewable sources of electricity in the Republic of North Macedonia.
2. To develop a methodology for studying the potential of solar radiation and simulating the production of electricity from photovoltaic systems on the territory of the Republic of North Macedonia.
3. To synthesize a scheme and model the operation of powerful photovoltaic power plants on the territory of the Republic of North Macedonia.
4. To model the operation and energy balance of the Republic of North Macedonia after being connected to the newly built photovoltaic power plants, with the aim of analyzing the changes in energy flows, energy losses and overvoltages in the power transmission network.
5. To carry out a technical-economic analysis of the construction of new photovoltaic power plants on the territory of the Republic of North Macedonia, depending on the expected prices on the electricity market in the following years.

Research methods:

The research methods used in solving the tasks set in the dissertation are: theoretical analysis, computer design, modeling and simulation studies, using methods of mathematical statistics for data processing. Conceptual electrotechnical projects, simulation of the mode of operation of two new FhPP and their connection with the energy system of the Republic of North Macedonia, as well as a technical-economic analysis of the profitability of their construction, which improves the efficiency and infrastructure of the electricity supply to the population, have been implemented.

Applicability:

The applicability of the dissertation work is related to the developed detailed variant projects of 2 photovoltaic plants on the territory of the Republic of North Macedonia with a total capacity of 60 MWp, using 4 different variants of technologies and orientation of the photovoltaic modules available on the market. A technical-economic analysis and evaluation of the profitability of the construction of the new 2 photovoltaic power plants was made, taking into account the dependence on the expected prices on the electricity market in the coming years. Studies of the potential of solar radiation for the production of electrical energy from photovoltaic power plants in the territory of the Republic of North Macedonia, as well as the synthesis of a model of the electricity system of the Republic of North Macedonia, enabling the analysis of changes in energy flows when new power plants are included, are good basis for the development of future projects for photovoltaic power plants and their connection in the power system.

Approbation of the dissertation work:

The main stages of the dissertation work's development are presented in five publications at international conferences and scientific publications, fully covering the minimum requirements regarding the considered criterion. Two of the papers were presented at the "Unitech" International Scientific Conference and two at a national conference „TechCo“, both of which are self-contained.

The publications have been published in peer-reviewed proceedings of the Unitech international scientific conference and a national conference „TechCo“ during the training period 2022-2023, as they actually represent a significant part of the content of the dissertation work. One of the publications was presented at an international scientific conference EEPES 2023 (Greece) and is published in the American Refereed Press AIP, which is referenced in Scopus с SJR. The publications present both a large part of the conducted research and the main conclusions of the dissertation work.

Structure and volume of the dissertation:

The dissertation includes a list of abbreviations used, an introduction, five chapters, a conclusion, a list of publications on the dissertation, a list of references and appendices. The total volume is 172 pages and was developed based on an analytical review of 96 literary sources and 43 Internet-based sources.

II. CONTENTS OF THE DISSERTATION

CHAPTER I. Study and analysis of energy capacities for electricity production and the role of renewable energy sources in improving the energy system in the Republic of North Macedonia

1.1. Explanation of the problem and definition of the study

The main goals of today's politics and economy are focused on energy. Energy reserves of fossil fuels are constantly decreasing, which is a prerequisite for rising energy prices. The increased need for energy, the requirements for technological development, the significant changes taking place in the world energy market contribute to paying special attention to producing energy from renewable sources. Considering the current situation with the available energy sources in North Macedonia, we can say that the country is facing serious energy problems that have a great impact on its development. As one of the reasons are the limited energy resources, which in turn make the country dependent on energy imports and are a prerequisite for a low level of energy security. [57], [59]

1.2. Energy balance of electricity in the Republic of North Macedonia

Table 1.1 shows the balance of electricity demand, supply and production for the period 2019 y. – 2021 y. (GWh).

Table 1.1. Energy balance for the period 2019-2021

GWh	2019 y.	2020 y.	2021 y.	2021/2020 (%)	2021/2019 (%)
Delivered into the power system	8 130	8 479	9 532	12,41	17,24
Production	5 658	5 128	5 285	3,07	-6,59
Largest producer	4 250	3 643	3 170	-12,98	-25,41
Other producers	1 059	1 091	1 705	56,22	61,00
Producers with preferential tariff	349	393	407	3,45	16,62
Producers with premium chosen tariff		0,056	3	5 276,15	
Total import	2 472	3 352	2 940	-12,29	18,93
Gross consumption	7 483	7 459	7 906	6,00	5,65
Net consumption	6 504	6 476	6 865	6,01	5,55
Direct consumers of transmission	963	957	924	-3,41	-4,05
Regulated supplier	3 807	3 562	3 688	3,53	-3,13
Other distribution consumers	1 734	1 957	2 252	15,10	29,87
Losses	979	983	1 041	5,90	6,33
Transmission	120	124	125	0,90	4,17
Distribution	859	859	916	6,62	6,64
Export	646	1 011	463	-54,21	-28,33
Net Import	1 825	2 341	2 621	11,97	43,62
% Import dependence	24,39	31,38	33,15		
Shares in the open market %	49,13	52,24	53,34		

Figure 1.1 shows the installed capacity and the share of individual technologies in the production of electricity in 2021 г. (MW и %).

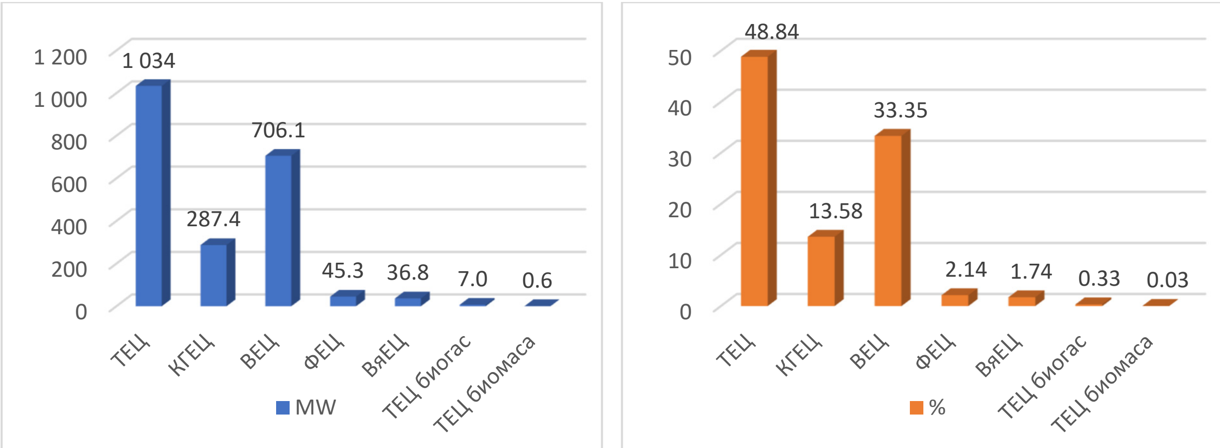


Figure 1.1. Installed capacity and share of individual technologies on electricity production in 2021. (MW и %)

Thermal power plants have the largest relative share - 48.84%, followed by hydropower plants - 33.35%, combined heat and power plants - 13.58% and all others - 4.23%.

In 2021, new power producers with an installed capacity of 14.2 MW were added to the power system and all of them were connected to the power distribution network. Most of the new power plants are photovoltaic plants with a total installed capacity of 14 MW, followed by small hydroelectric plants with a total installed capacity of 0.2 MW.

In 2021, four companies operate power plants with an installed unit capacity of more than 10 MW: JSC Elektrani na North Macedonia - Skopje, JSC TE-TO Skopje, JSC TEC Negotino and EVN Makedonija Elektrani DOOEL Skopje. The largest producer of electricity in the Republic of North Macedonia in 2021 remains AD ESM Skopje, state-owned by the government of the Republic of North Macedonia. Table 1.2 shows the installed capacity and electricity production in 2021.

Table 1.2. Installed capacity and production in 2021

Producers	Number of power plant	Installed capacity (MW)	Participation (%)	Production (GWh)	Participation (%)
JSC ESM Skopje	15	1 478,61	69,83	3 273,60	61,95
TPP	4	824,00	38,91	2 078,3	39,33
HPP	8	557,40	26,32	1 078,6	20,41
WPP	1	36,80	1,74	103,3	1,95
CGPP	2	60,41	2,85	13,9	0,26
JSP Negotino-TPP	1	210,00	9,92	27,08	0,51
TPP	1	210,00	9,92	27,08	0,51
JSP TE-TO	1	227,00	10,72	1 503,20	28,45
КГЕЦ	1	227,00	10,72	1 503,20	28,45
EVN Power Plant	14	61,60	2,91	148,71	2,81
SHPP	11	58,56	2,77	145,95	2,76
PvPP	3	3,00	0,14	2,76	0,05
Others	321	139,79	6,60	331,84	6,28
SHPP	98	89,89	4,25	229,14	3,85%
PvPP	219	42,30	1,99	48,70	0,92%
Biogas	3	7,00	0,22	54	1,12%
Biomass	1	0.60	0,03	0	0,00%
Total	352	2 117,39	100,00%	5 284,43	100,00%

1.3. Electricity production in the Republic of North Macedonia

The electricity produced in the Republic of North Macedonia is obtained from thermal power plants, hydroelectric power plants, cogeneration plants, wind power plants, biogas power plants, photovoltaic power plants and biomass power plants. Figure 1.2 shows the percentage share of individual technologies in the production of electricity in 2021, of which it is established that in 2021 the largest share of the electricity produced is the thermal power plants with 39.83%, followed by the cogeneration plants for the production of electricity and thermal energy with a share of 28.70%, hydroelectric plants with 27.51%, followed by all others with a share of 3.96%.

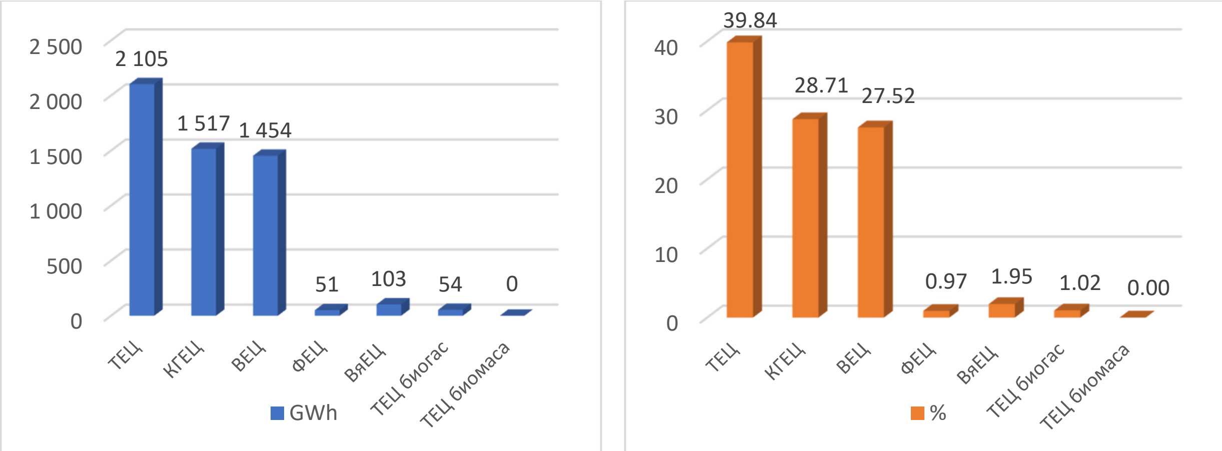


Figure 1.2 Share of individual technologies in electricity production in 2021 y. (GWh, %)

Electricity production from renewable RES energy sources is variable on an annual basis and depends primarily on hydrological capacity. In the total electricity production for 2021, the renewable energy sources participate with 31.46%, which is 14.72% more than in 2020, while the electricity production from thermal power plants takes part with 68.54%, which is 17. 12% less than 2020.

Table 1.3 shows the electricity production in the Republic of North Macedonia for a period of ten years from 2012 to 2021. From the data provide, it can be concluded that there is a significant decline in domestic electricity production. In 2021, the electricity produced in the country was 5 284,8 GWh, while in 2012 it was 5 806,6 GWh, a decrease of 8.96%. The highest electricity production was recorded in 2010, 6 744,2 GWh, indicating that the production decline in 2020 is 21.64%.

Table 1.3. Electricity production from 2022 to 2021

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
GWh	5 806,6	5 676,4	4 982,3	5 271,5	5 302,7	5 229,0	5 287,5	5 655,5	5 128,3	5 284,8
JSC ESM (previously JSC ELEM)	5 370,1	5 113,0	4 535,0	4 741,8	4 299,9	4 080,1	4 114,3	4 283,7	3 642,8	3 273,6
Production TPP	4 475,7	3 742,6	3 506,4	3 092,7	2 699,1	3 145,1	2 613,0	3 293,8	2 509,8	2 078,3
TPP Bitola 1,2,3	3 971,0	3 572,6	3 316,8	2 986,2	2 672,3	3 076,1	2 545,3	3 200,9	2 415,1	1 864,4
TPP Oslomej	504,7	170,0	189,6	106,5	26,8	69,0	67,7	92,9	94,7	213,9
Production of RES	887,5	1 362,5	958,2	1 528,3	1 490,1	816,1	1 391,1	879,5	965,3	1 078,6
HPP Mavrovo	263,2	287,0	398,0	438,9	553,2	393,3	433,5	418,0	386,7	423,5
HPP Spilje	239,7	393,3	190,3	303,7	353,2	157,5	366,7	172,6	204,6	257,9
HPP Tikvesh	104,8	211,0	116,1	312,8	145,2	63,1	138,1	67,5	98,6	90,5
HPP Globochica	169,8	247,6	136,2	225,5	232,6	96,9	229,3	112,7	137,7	160,5
HPP Kozjak	97,8	184,0	80,4	171,6	142,8	71,0	156,7	73,1	95,8	97,9
HPP Sveta Petka	12,2	39,6	37,2	75,8	63,1	34,3	66,8	35,5	41,9	48,2
WPP Bogdanci	0,0	0,0	70,4	120,8	109,5	110,5	97,3	101,8	116,9	103,3
CGPP Energetika - Zelezara	6,8	7,9	0,0	0,0	1,2	8,4	12,9	8,6	8	0
CGPP Kogel	2,2	4,3	1,2	0,7	3,7	7,0	0,0	0,0	42,8	13,9
TPP Negotino	0	0	0	0	0	0	0	0	0	27
CGPP TE-TO	280,1	340,8	189,8	177,8	550,1	794,7	716,6	987,0	1 067,8	1 503,2
SHPP	151,2	209,6	241,9	308,4	389,3	271,8	379,2	304,0	322,05	375
PhPP	3,1	8,7	14,3	22,6	23,7	23,9	23,3	25,6	37,3	52
TPP from biogas	0,0	0,0	0,0	20,2	36,0	51,6	54,1	55,1	57,3	54

Note: The presented data do not include the amounts of electricity of JSC ESM Skopje, used for its own needs, as well as for the needs of the mines.

The reason for the decline in the local electricity production is that the largest producer JSC ESM Skopje did not invest enough in new production capacities. In 2021, JSC ESM Skopje alone produced 3 273,6 GWh, and in 2012, 5 370,1 GWh were produced, which is 60,96% less. There was a significant drop in production in thermal power plants, which produced 2 078,3 GWh in 2021 and 4 475,7 GWh in 2012, which is 46,44% less.

In the Republic of North Macedonia, in the last 3 years, there has been considerable interest in the construction of large wind farms in accordance with the Law on Strategic Investments, however, their construction takes a long period of time. The quotas under the preferential tariff for wind power plants have been fulfilled. There is interest from private investors in the construction of photovoltaic plants, but with small capacities of up to 2 MW, being not enough to cover the lack of electricity. For these reasons, it is necessary to build new RES capacities, which will reduce the import of electricity.

1.4. Electricity consumption in the Republic of North Macedonia

Electricity consumption in 2021 is 6 865 GWh, of which 924 GWh are from plants that were operating as consumers (did not produce electricity, due to repairs, defects, etc.). In 2021, electricity consumption decreased by 3,41% compared to 2020, amounting to 957 GWh. From the analysis of the electricity balance data, it can be concluded that in 2021 there were no significant changes in electricity consumption compared to 2020.

Electricity consumption in 2021 by consumers connected to electricity distribution networks is 5 941 GWh, which is a significant increase of 7,65% or 422 GWh compared to electricity consumption in 2020, which is 5 519 GWh. The reason for the increase in total electricity consumption is the recovery of economic and social processes, mitigation of measures related to stopping the spread of COVID-19, etc.

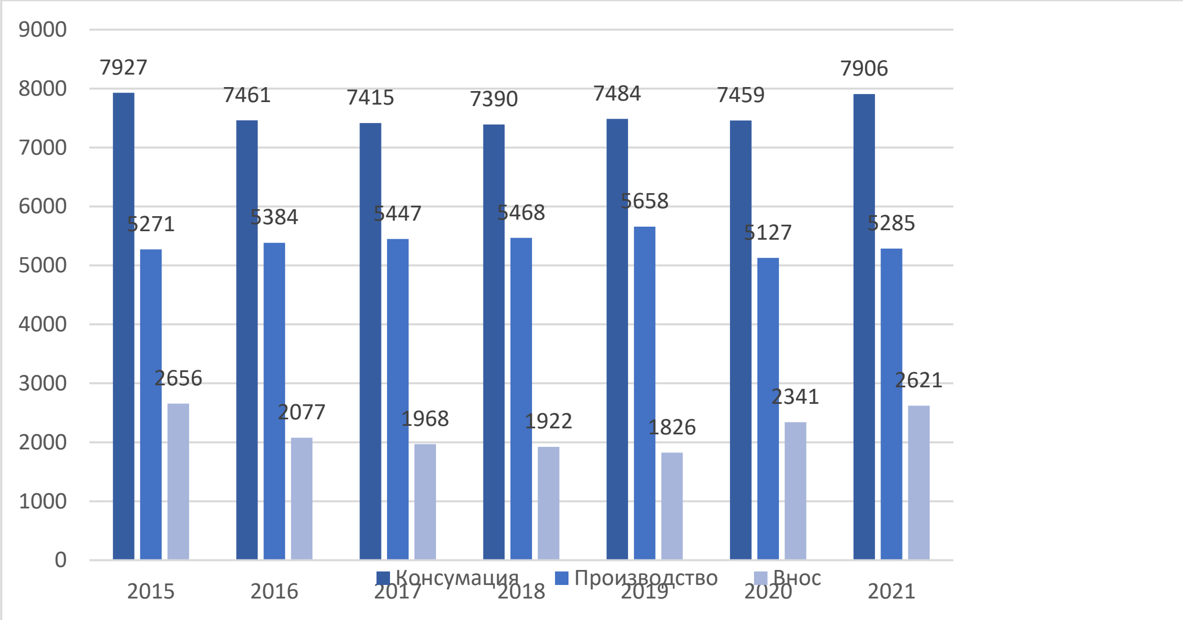
1.5. Intersystem physical flows of electricity with other countries

North Macedonia does not have sufficient generation capacity to meet the needs of electricity consumers, so the country is dependent on imports. In the last ten years, the amount of imported electricity has been increasing more and more. Electricity imports increased from 20% to 33,15%. of the total gross electricity consumption. This means that one third of the required electricity is bought on the free market. The import dependence of the Republic of North Macedonia is determined on the basis of the ratio between the internal production of electricity and the gross consumption of electricity, taking into account the consumption of electricity by end users, including the electricity needed to cover electricity losses in the electricity transmission network and in the electricity distribution networks.

Figure 1.3 shows the production of electricity intended for electricity consumers in the Republic of North Macedonia, consumption and import of electricity.

In 2021, the net electricity import was the highest at 2,621 GWh, accounting for 33.15% of the total gross electricity consumption, while in 2020, it was 31,38% of the total gross electricity consumption. In 2019, imports were 24,4% and in 2018 they were 26,01% of the total consumption. In 2021, an increase of 11,96% was reported, compared to the import in 2020, and compared to 2019, an increase of 43,53% was reported. This increase in imports is due to a significant decrease in domestic electricity production and a concomitant increase in gross electricity consumption.

In addition to electricity being bought in the Republic of North Macedonia, electricity is also sold on the free market. Surpluses of own electricity production, which occur especially at night, are sold on the open market, but unfortunately these quantities are very small compared to the imported quantities and at a very low price. Surplus electricity produced by domestic producers is sold to licensed traders who sell the electricity abroad. The export of electricity produced in the Republic of North Macedonia in 2021 was 359 GWh, which is a decrease of 44% compared to 2020, when the export was 639 GWh. [A3]



A)

B)

Figure 1.3. Consumption, production, n MW net import of electricity and share of net import in electricity consumption for the period from 2015 to 2021: A) in GWh; B) - %.

1.6. RES in the Republic of North Macedonia

Renewable electricity sources include large hydroelectric power plants with an installed capacity of more than 10 MW, small hydroelectric power plants with an installed capacity of up to 1 MW, wind power plants, photovoltaic power plants, biogas power plants and biomass power plants. The total installed power from renewable electricity sources is 795 MW, which represents 37,57% of the total installed power in North Macedonia, and in the total electricity production in 2021, they participate with 1 662 GWh, that is, with 31,45%. Considering the geographical position of the Republic of North Macedonia, located on the Balkan Peninsula in Southeast Europe, as well as the favorable climate, the energy potential of renewable sources is not fully utilized, in particular, solar energy, considering that the Republic of North Macedonia has many sunny days and the total solar radiation is between 1300 and 1700 kWh/m^2/year. In order to increase the installed capacity, as well as the production of electricity, the government of the Republic of North Macedonia is taking a number of measures to support and develop RES.[6]

1.7. Installed capacities of renewable sources of electricity in the Republic of North Macedonia

Electricity producers from renewable energy sources in the Republic of North Macedonia consist of large hydroelectric power plants with an installed capacity of more than 10 MW, small hydroelectric power plants with an installed capacity of less than 10 MW, wind power plants, photovoltaic power plants, biogas thermal power plants and biomass thermal power plants. From the energy balance of the Republic of North Macedonia, the total installed capacity in the Republic of North Macedonia is 2 117 MW, of which 1 034 MW is the installed capacity of thermal power plants, the installed capacity of cogeneration plants is 287 MW and the installed capacity from renewable sources is 795 MW. The percentage participation of thermal power plants in the total installed capacity in 2021 is 48,85%, of cogeneration plants is 13.58% and of renewable sources is 35,57%. The percentage representation of renewable energy sources also takes into account the installed capacities of large hydroelectric plants. In 2021, 5 284 GWh of electricity was produced, of which 2 105 GWh was produced by thermal power plants, 1 517 GWh by cogeneration plants and 1 662 GWh by renewable sources. The percentage share of electricity produced by thermal power plants is 39,84%, from cogeneration plants 28,71% and from RES 31,45%.[10]

Table 1.4 shows the installed capacities and their production of power plants that use renewable sources, divided by technology.

Table1.4. Installed capacity and electricity production from renewable energy sources in 2021, by technology

Type of RES	Number of RES	Installed capacity (MW)	Participation (%)	Production (GWh)	Participation (%)
RES	344	795	37,57%	1 662	31,45%
HPP	10	587	73,76%	1 132	68,12%
WPP	1	36,8	4,63%	103	6,20%
SHPP	107	119	14,97%	321	19,34%
PhPP	222	45	5,69%	51,46	3,10%
PP from biogas	3	7	0,88%	54	3,25%
PP from biomass	1	1	0,08%	0	0,00%

In the Republic of North Macedonia, there are a total of 344 RES producers, of which 202 use a preferential tariff, 7 use a premium, while 135 plants do not use measures to support electricity production, i.e. sells the produced electricity on the free market.

1.8. Preferential tariffs – feed in tariffs for RES in North Macedonia

The types of technologies with feed-in tariff, the upper limit of the installed capacity of the plant, the amount and period of use of the feed-in tariffs, as well as the prescribed total installed capacity of the plants for which the feed-in tariffs are granted are presented in a table 1.5.

Table 1.5 Preferential tariffs established in the Decree on measures to support the production of electricity from renewable energy sources and the prescribed total installed capacity of power plants

RES	Upper limit of the installed capacity of the power plant	Prices for feed in tariffs	Time period for feed in tariffs	Prescribed Total Installed Power
PhPP	≤0,05 MW	460 €/MWh	20 year	
		380 €/MWh	15 year	
		300 €/MWh		3,66 MW
		160 €/MWh		
		120 €/MWh		
	0,05<MW≤1MW	410 €/MWh	20 year	
		260 €/MWh	15 year	13 MW
SHPP	10 MW	for the monthly amount of delivered electricity by blocks : I block : 120 €/MWh (≤ 85 000 kWh) II blocks : 80 €/MWh (> 85 000 и ≤ 170 000 kWh) III block : 60 €/MWh (> 170 000 и ≤ 350 000 kWh) IV block: 50 €/MWh (> 350 000 и ≤ 700 000 kWh) V blocks : 45 €/MWh (> 700 000 kWh)	20 year	
WPP	50 MW	89 €/MWh	20 year	160 MW
TPP from biomass	≤ 3 MW(from 30.06.2021) ≤ 1 MW(to 1.07.2021)	180 €/MWh	15 year	10 MW
TPP from biogas	≤ 3 MW(from 30.06.2021) ≤ 1 MW (to 1.07.2021)	180 €/MWh	15 year	20 MW

In 2021, the total number of renewable sources that use a preferential tariff is 202, and the total installed capacity is 148 MW, and the produced amounts of electricity are 407 GWh.

Table 1.6. Installed capacity, electricity production and funds paid to preferential producers using a preferential tariff-feed in tariff 202 by types of technologies

RES with feed in tariff	number	Installed capacity (MW)	Participation (%)	Production (GWh)	Participation (%)
SHPP	96	87	58,92%	227	55,85%
WPP	1	36,8	24,76%	103	25,39%
TPP from biomass	1	0,6	0,40%	0	0,00%
TPP from biogas	3	7	4,71%	53	13,23%
PhPV	101	16,67	11,21%	22	5,53%
Total	202	148	100%	407	100%

1.9. Modern systems for production and management of electricity

The liberalization of the electricity market, the increase in the share of energy generated from RES, as well as the progress of information technologies and their increasing application in the electricity system are the main reasons for the introduction of the development of the concept of a smart grid (IG). With it, the behavior and actions of all users and generators that make up it can be effectively monitored and managed.

The main objectives of IG are to ensure an economically efficient, sustainable energy system with low losses and high levels of quality and security of supply.

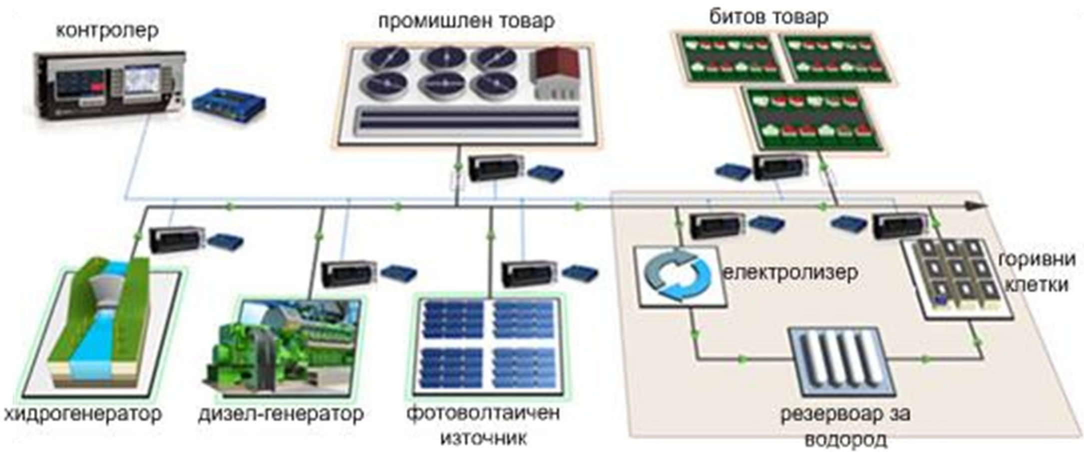


Figure 1.4. Example diagram of a smart grid

1.10. Analysis of the implementation of modern systems for the production and management of electrical energy in the Republic of North Macedonia

PhPPs participate with a small percentage in the total installed capacity and in the total production of electricity. By 2021, anyone of the PhPP was connected to the transmission electricity grid. Taking into account the stability of the electricity transmission grid of JSC MEPSO in the Republic of North Macedonia, there are conditions for the connection of PhPP to the electricity transmission network, especially in the western region. In 2022 and 2023, a large number of PhPPs with small capacities connected to the electricity distribution grid were built, concentrated especially in the eastern part of the Republic of North Macedonia, Shtip, Berovo, which created a problem that the consumption was lower than the electricity production, thus causing additional problems for JSC MEPSO. The construction of PvPP in the electricity distribution network in the western region of the RNM is still small, which means that the newly planned PhPP Bitola and PhPP Oslomei - 2 will be connected to the power grid without any problem.

1.11. Conclusions to the first chapter

The following conclusions can be drawn from the study and analysis of the energy capacities for electricity production and the role of renewable energy sources in the energy system of the Republic of North Macedonia carried out in the first chapter:

1. The net consumption of electricity, including losses in the electricity transmission and distribution network in 2021 is 6 865 GWh. It has been on an upward trend in the last 3 years due to the slight increase in the number of inhabitants as well as the new industrial users.

2. Domestic production in 2021 amounts to 5 285 GWh, which includes the production of electricity by the largest local producer JSC ESM and the production of other private producers is increasing. The production of electricity by the largest electricity producer JSC ESM is in the amount of 3 170 GWh, and there is a tendency for a large reduction in the electricity produced by thermal power plants, as there is no investment in other energy capacities.

3. Net import in 2021 amounts to 2 621 GWh and is on an upward trend due to reduced domestic electricity production.

4. The total electricity production in 2021 from renewable energy sources, including large hydropower plants, is 1 662 GWh. It is in an increasing trend, especially in the part of production from hydroelectric power plants.

5. Electricity production from PhPP in 2021 is 51.46 GWh, with a minimal increase.

6. The use of the sun as an energy resource is relatively small, although the solar radiation on the territory of the RNM is very high and amounts to 1300 - 1800 kWh/m^2/year.

7. Electricity production can be increased most rapidly by building new power plants.

8. In order to follow the RNM Energy Development Strategy, it is best to build power plants with larger capacities – over 10 MW.

9. The construction of a PhPP with a smaller capacity and connection to the electricity distribution network is not the best solution in the RNM, since construction permits are issued by municipalities that do not follow the Development Strategy.

1.12. Purpose and tasks of the dissertation work

The main goal of the dissertation is to analyze the possibilities for implementing new photovoltaic power plants in the electricity system of the Republic of North Macedonia. To achieve the main goal, it is necessary to complete the following tasks:

1. To study good practices from the neighboring countries of the region and analyze the energy balance when implementing renewable sources of electricity in the Republic of North Macedonia.

2. To develop a methodology for studying the potential of solar radiation and simulating electricity production from photovoltaic systems on the territory of the Republic of North Macedonia.

3. To synthesize a scheme and model the operation of powerful photovoltaic plants on the territory of the Republic of North Macedonia.

4. To model the work and the energy balance of the Republic of North Macedonia after the accession of the newly built photovoltaic power plants, in order to analyze the changes in energy flows, energy losses and overvoltages in the power transmission network.

5. To carry out a technical and economic analysis of the construction of new photovoltaic power plants on the territory of the Republic of North Macedonia, depending on the expected prices that may reach in the coming years on the electricity market.

CHAPTER II. Study and analysis of the energy balance and the implementation of renewable sources of electricity in the Republic of Bulgaria, the Republic of Serbia and the Republic of Croatia

2.1. Energy balance of the Republic of Bulgaria

The electrical energy produced in the Republic of Bulgaria is obtained from NPP, TPPs, HPPs, CGPPs, WPPs, FhPPs, and biomass plants. The total installed generation capacity connected to the electricity transmission network is 13 505 MW (Table 2.1), of which the largest installed capacity is the lignite-fired thermal power plant 4 119 MW, followed by the total installed capacity of large hydroelectric power plants 3 214 MW and the NPP Kozloduy power plant with an installed capacity of 2 000 MW. In fourth place are photovoltaic power plants with 1 726 MW, in fifth place are gas thermal power plants with an installed capacity of 1 307 MW. In sixth place wind power plants with an installed capacity of 705 MW. In seventh place, thermal power plants - black coal with 356 MW and in eighth place biomass power plants with 77 MW in 2022 (Table 2.1).[12], [70], [71].

Table 2.1. Installed capacity and electricity production through 2022 in the Republic of Bulgaria in the power grid

Producers	Installed capacity (MW)	Participation (%)	Production (GWh)	Participation (%)
NPP	2 000	14,8%	16 464	32,55%
TPP - Lignite coal-fired	4 119	30,5%		
TPP of coal	356	2,6%		
CGPP	1 307	9,7%	26 463	52,32%
HPP	3 214	23,8%	3 811	7,53%
WPP	705	5,2%	1 499	2,96%
PhPP	1 726	12,8%	2 023	4%
TPP from biogas	77	0,6%	318	0,63%
Total	13 505	100,00%	50 579	100,00%

Table 2.2. Gross electricity consumption in the Republic of Bulgaria in 2022

GROSS ELECTRICITY CONSUMPTION		
Type consumption	GWh	Percentage 2022/2021, %
Own needs for Power Plant	5 228	6,8%
Transmission losses	876	-0,3%
Consumption of pumps	49	-86,9%
Final power consumption	32 180	-2,1%
Total	38 334	-1,7%

Gross electricity consumption in the Republic of Bulgaria in 2022, total electricity consumption is 38 334 GWh (Table 2.2), final electricity consumption 32 180 GWh (83.85%), own needs of the power plant 5 228 GWh (13.64%), transmission losses 876 GWh (2.28%), and pump consumption 49 GWh (0.22%). [72], [74]

2.2. Energy balance in Republic of Serbia

The total installed generating capacity in the Republic of Serbia is 8 516 MW, excluding the production capacity on the territory of Kosovo. The largest electricity producer is JSC EPS, which owns lignite-fired thermal power plants with an installed capacity of 4 429 MW, then large hydroelectric power plants with an installed capacity of 2 941 MW (Table 2.3), natural gas or fuel oil CGPP 330 MW , as well as the owner of eighteen small hydropower plants, with a total installed capacity of 41 MW.[13]

Table 2.3. Installed capacity and electricity production in 2021 in the Republic of Serbia excluding the production capacity of Kosovo

technology	Installed Capacity (MW)
HPP	2 941
TPP (coal)	4 429
CGPP - heating plants (gas, fuel oil)	526
TPP from gas	-
NPP	-
WPP	373
SHPP owners of ChP EPS	41
SPPP from other owners	206
Total installed capacity	8 516

The total installed generation capacity that is connected to the electricity transmission network is 8 269 MW, producing a total of 34 758 GWh of electricity per year (Table 2.4).

The total installed generation capacity that is connected to the electricity distribution network is 246 MW, and they produce a total of 898 GWh of electricity per year (Table 2.5). The total installed production capacity, which is connected to the electricity transmission network, is 8,269 MW, producing a total of 34,758 GWh of electricity per year (Table 2.4).

The total installed generation capacity that is connected to the electricity distribution network is 246 MW, and they produce a total of 898 GWh of electricity per year (Table 2.5).

Table 2.4. Total installed capacity of power plants that are connected to the power transmission system

Technologies	Number of Power Plant	Installed capacity (MW)	Electricity production (GWh)
HPP	14	2 941	11 587
Run-of-river hydroelectric plants	5	1 980	9 654
Accumulation hydroelectric power plants	8	347	1 233
Reversible hydroelectric power plants	1	614	699
TPP	7	4 429	21 537
CGPP	3	526	630
WPP	4	373	1 004
PhPP	0	0	0
TOTAL	28	8 269	34 758

Table 2.5. Total installed capacity of power plants connected to the power distribution system

Technologies	Number of Power Plant	Installed capacity (MW)	Electricity production (GWh)
SHPP	149	127	339
TPP of biomass	2	3	23
TPF of biogas	35	36	221
WPP	4	25	66
PhPP -TOTAL	145	12	14
PhPP on land	18	7	8
PhPP on the rooftop	127	5	5
Fossil fuel power plants	16	39	225
Others	2	3	10
TOTAL	353	246	898

Table 2.6. Production and consumption of electricity in the period 2017-2021 excluding the territory of Kosovo

Year	2017	2018	2019	2020	2021
	GWh	GWh	GWh	GWh	GWh
HPP	9 477	11 031	9 884	9 419	11 587
TPP	24 240	22 954	23 169	24 331	21 537
CGPP	185	238	337	192	630
WPP		85	830	905	1 004
Others PP	538	642	612	693	898
Total production	34 441	34 950	34 832	35 540	35 656
Import of Electricity Transmission System (ETS) and suppliers for the needs of traders in RS	3 397	4 582	4 260	4 444	5 444
ETS	37 981	39 626	39 124	39 987	41 100
ETS export and supplier - electricity. produced and purchased	2 186	4 246	3 940	4 708	4 792
need for a pump in Serbia	944	1 070	1 102	1 082	961
the rest to Kosovo	458	313	275	337	52
Net consumption needs a pump and the rest to Kosovo	35 722	35 380	35 184	35 273	36 203
Net consumption	34 320	33 997	33 807	33 853	35 217
Transmission losses	952	859	806	798	845
Distribution losses	3 953	3 664	3 527	3 587	3 636
Total losses	4 805	4 532	4 333	4 385	4 481
Total losses in %	13,9%	13,3%	12,8%	13,0%	12.7
TOTAL CONSUMPTION	29 515	29 465	29.474	29 468	30 862

In 2021, the electricity produced in the Republic of Serbia is 35 656 GWh, production from TPP is 60,4%, production from HPP is 32,5%, production from is CGPP is 1,8%, production from WPP is 2,8%.

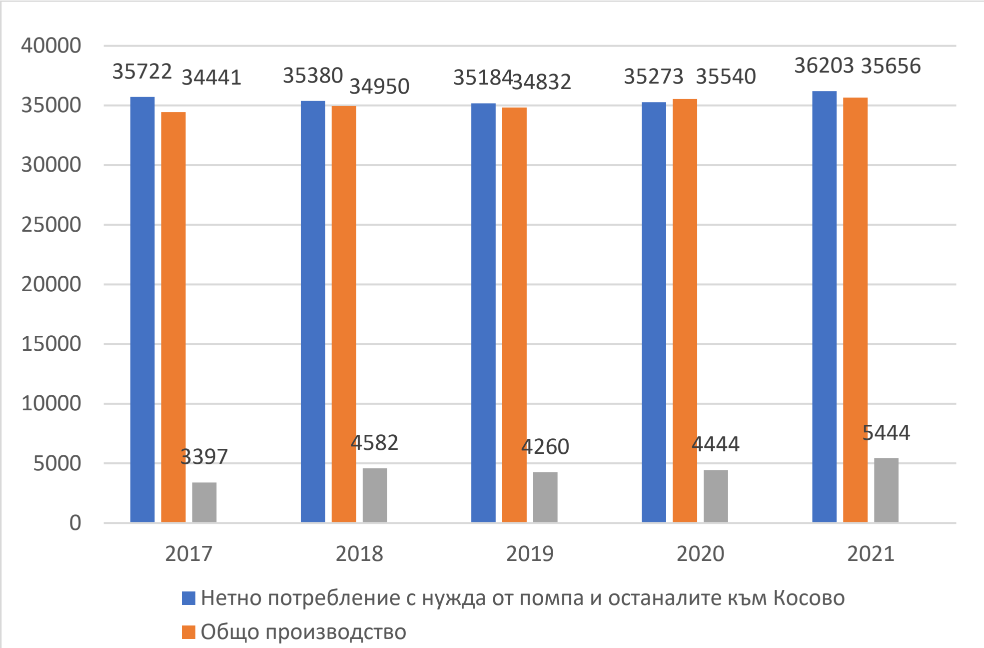


Figure 2.1. Balance of electricity production in the Republic of Serbia in the period 2017-2021

From the energy balance, it may be concluded that the consumption of electricity is constantly increasing. Net electricity consumption in 2021 is 35 217 GWh. In 2021, 5 444 GWh of electricity was imported, which represents 17,64% of the total electricity consumption, which is 30 862 GWh, and of the net consumption with the need for a pump and the rest to Kosovo, 36 203 GWh represents 15,04%. Also in 2021, there are electricity exports of 5 806 GWh (Table 2.6). The difference between imports and exports is 366 GWh. In the future, measures should be taken to reduce the percentage of imported electricity, and export should be done in the evening hours, when electricity consumption is the least, so there is a surplus that is sold on the open market. Electricity prices at night are significantly lower than during the day, as there is more supply than demand during this period. Figure 2.1 shows the gross balance of electricity production from the Republic of Serbia, as well as net consumption together with the needs provided to Kosovo, total production and import in 2017-2021.

2.3. Energy balance in the Republic of Croatia

The total installed capacity in the Republic of Croatia is 5 306 MW (Table 2.7). Thermal power plants have a total installed capacity of 2 044 MW, which represents 38,5% of the total installed capacity. Large hydropower plants have a capacity of 2 202 MW, which represents 41,5% of the total installed capacity. Wind power plants account for 795 MW, accounting for 15%, and other renewable sources of electricity for 265 MW, accounting for 5% of the total installed capacity. The Republic of Croatia also owns 50% of the TEC Krsko nuclear power plant.[14]

The installed capacity of all renewable energy sources, hydroelectric power plants, wind power plants, biomass power plants, biogas power plants, photovoltaic power plants and geothermal power plants, has a total installed capacity of 3 262 MW, which represents 61,5% of the total installed capacity in the Republic Croatia.

The total electricity consumed in the Republic of Croatia in 2020 was 17 272 GWh (Table 2.9). The most produced electricity was realized by domestic producers and was 12 216 GWh, which accounted for 70,7%, and 5 056 GWh was imported electricity, which accounted for 29,3%. Electricity imports include the amount of electricity produced by NPP Krsko located in the Republic of Slovenia, and the Republic of Croatia has a 50% share in the installed capacity as well as the amount of electricity produced.

Table 2.7. Installed capacity in the Republic of Croatia in 2020

Technologies	Installed Capacity (MW)	Participation (%)
TPP	2 044	38,5%
HPP	2 202	41,5%
WPP	795	15%
TPP from biomass	92	1,74%
TPP from biogas	55	1,01%
PhPP	109	2,05%
Geothermal power plants	10	0,19%
TOTAL	5 306	100%

Large hydroelectric plants alone produced 5 361 GWh, representing 43,9% of the total electricity generated. Thermal power plants produced 4 084 GWh in 2020, accounting for 34,34%. Wind farms Power Plant produced 1 721 GWh, accounting for 14,08%. Biomass power plants 502 GWh, representing 4,11%. Biogas power plants 376 GWh, representing 3.09%, photovoltaic power plants 96 GWh, representing 0,78%. Geothermal power plants produced 76 GWh, i.e. 0,62% (Table 2.8).

Table 2.8. Electricity produced in the Republic of Croatia in 2020

Technologies	Production (GWh)	Percentage participation (%)
TPP	4 084	34,34%
HPP	5 361	43,9%
WPP	1 721	14,08%
TPP from biomass	502	4,11%
TPP from biogas	378	3,09%
PhPP	96	0,78%
GtPP	76	0,62%
TOTAL	12 216	100%

Table 2.9. Electricity balance in the Republic of Croatia 2019, 2021 in GWh

	Energy balance	2019 (GWh)	2020 (GWh)
1	Total production	12 006	12 216
2	Import	11 400	10 490
3	Total (1+2)	23 406	22 706
4	Export	5 237	5 434
5	Physical net import (2-4)	6 163	5 056
6	Total consumption (3-4)	18 169	17 272
7	Produced amount of EE transferred from the distribution network	1 348	1 415
8	Transmission losses	388	373
9	Consumption (6-7-8)	16 433	15 484
10	Delivery to end users connected to the electricity transmission network and own consumption of the plants	902	826
11	Compensation	176	231
12	Net supplies in the electricity distribution network (9-10-11)	15 355	14 427

Table 2.10. Decisions of RES producers following a preferential tariff for the period from 2007 to 2020.

Technologies	Numb er	Installed capacity ([MW]
PhPP	230	24,39
HPP	39	2 095,51
WPP	31	749,80
TPP of biomass	39	86,17
GtPP	1	10,00
TPP of biogas	42	48,65
CGPP	6	112,94
Power plants from other renewable sources (landfill gas, waste water treatment gas plants, etc.)	1	2,50
TOTAL	389	3 129,97

The measures to support renewable energy sources applied in the Republic of Croatia are preferential tariffs and premiums. Preferential tariffs have been in place since 2007, while premiums for renewables and high-efficiency cogeneration plants have been in place since 2020. The Energy Regulatory Commission is responsible for providing solutions for renewable energy producers who use feed-in tariffs. The total amount of capacity of RES producers that follow a preferential tariff for the period from 2007 to 2020 is 3 129,97 MW (Table 2.10). A total quota of premiums for renewable energy sources and for highly efficient cogeneration plants is presented in Table 2.11. In Table 2.12. electricity production from RES under a preferential tariff and funds used in 2020 are presented.

Table 2.11. General quota of premiums for renewable energy sources and for high-efficiency cogeneration plants

Groups	Types of power plants from different types of renewable sources, distributed according to installed capacity	Capacity (MW)
1.1	PhPP with capacity: 50 kW < P < 500 kW	210
1.2	PhPP with capacity: 500 kW < P < 10 MW	240
1.3	PhPP with capacity above 10 MW	625
2.1	SHPP with capacity until 50 kW	4
2.2	SHPP with capacity: 50 kW < P < 500 kW	10
2.3	SHPP with capacity: 500 kW < P < 10 MW	10
3.1	WPP with capacity above 3 MW	1 050
4.1	TPP of biomass with capacity: 50 kW < P < 500 kW	6
4.2	TPP of biomass with capacity: 500 kW < P < 2 MW	20
4.3	TPP of biomass with capacity: 2 MW < P < 5 MW	15
5.1	GtPP with capacity above 500 kW	20
6.1	TPP of biogas with capacity: 50 kW < P < 500 kW	15
6.2	TPP of biogas with capacity: 500 kW < P < 2 MW	30
7.1	Innovative technologies for electricity production approved in the European Union	10

Table 2.12. Production of electricity from RES under a preferential tariff and funds used in 2020.

Technologies	Number	Capacity (MW)	% Participation	Production (MWh)	Part in the production	Payout share
PhPP	1 229	53,4	5,2%	73 206	2,2%	4,7%
SHPP	14	5,9	0,6%	25 000	0,8%	0,8%
WPPP	26	717,8	69,4%	1 671 358	50,8%	42,1%
TEC of biomass	39	86,2	8,3%	506 931	15,4%	23,0%
GtPP	1	10,0	1,0%	76 233	2,3%	4,0%
TEC of biogas	41	45,9	4,4%	354 800	10,8%	15,3%
Waste gas power plants, etc.	1	2,5	0,2%	13	0,0%	0,0%
CGPP	6	113,3	10,9%	579 767	17,6%	10,1%
TOTAL	1 357	1 035,0	-	3 287 307	-	-

In May 2020, the Order on the quota premiums for RES and highly efficient combined power plants was adopted. With its entry into force, the total power for all types of renewable energy sources, as well as for highly efficient combined power plants, is determined. The total quota for all types of premiums is 2 265 MW.

2.4. Analysis of energy balances and PhPP representation in the Republic of North Macedonia, the Republic of Bulgaria, the Republic of Croatia and the Republic of Serbia

The comparative analysis of the energy balances for all the countries considered, the Republic of North Macedonia, the Republic of Bulgaria, the Republic of Serbia and the Republic of Croatia, it may be concluded that the Republic of Bulgaria has the highest relative share of PhPP compared to the installed capacity, namely 12,8 % and with the largest percentage participation in the total electricity produced with 4%, followed by the Republic of North Macedonia, the Republic of Croatia and the Republic of Serbia - Figure 2.2.

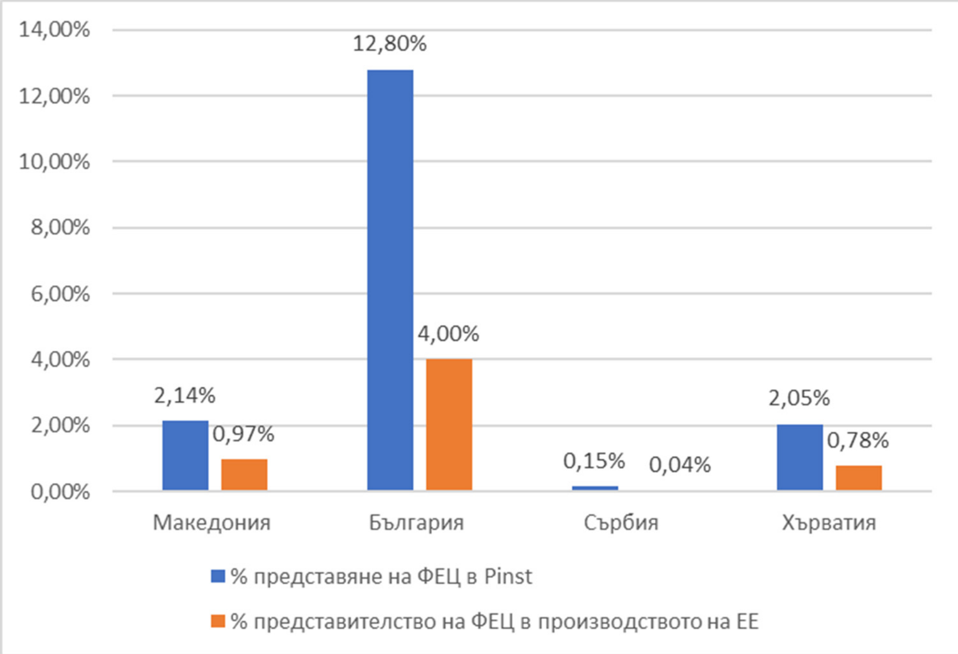


Figure 2.2. Application of PhPP in the energy balance of the countries of the Balkan region

2.5. Conclusions to Chapter Two

The following conclusions can be drawn from the performed theoretical study of energy balance and the prerequisites for the implementation of renewable sources of electricity:

1. In the Republic of Bulgaria, the electric power system has implemented nuclear power plants, a fairly large percentage of thermal power plants that use different fuels, then there are large hydroelectric power plants, then renewable energy sources. Renewable energy sources, including large hydroelectric plants, form 18,12% of the total production in the Republic of Bulgaria.

2. 1 726 MW of photovoltaic plants have been connected to the energy system of the Republic of Bulgaria, and the percentage of the installed capacities is about 12,8%. The electricity production of photovoltaic plants in 2022 is 2 023 GWh, and the percentage in gross production is 4%.

3. The energy crisis in the Republic of Bulgaria is not felt because there is a very small shortage of electricity. Currently, the electricity balance is in good shape, as a large percentage of the electricity generated is from nuclear power plants as well as thermal power plants.

4. In the Republic of Serbia, there is no representation of nuclear power plants in the total production of electricity, thermal power plants have the largest representation and it is 60,4%, followed by hydropower plants.

5. Renewable energy sources in the Republic of Serbia account for 36,61% of the total electricity produced, which is a really big percentage. This percentage also includes the production of electricity from large hydroelectric plants.

6. There are no power plants connected to the power grid in the Republic of Serbia. The PhPP are connected only to the electricity distribution network with a total installed capacity of 12 MW and produce only 14 GWh. Imports in the Republic of Serbia are 17,64%, while exports are 18,81%. The difference between imports and exports is 1,17%, which is not a worrying percentage.

7. Electricity produced by thermal power plants is 34,34%, which means that the Republic of Croatia is taking significant steps in terms of the Green Energy Package. Renewable sources of electricity are represented by 65,66% in the total electricity production. Net imports in the Republic of Croatia are 29,27% of total consumption, while exports are 31,46%. The percentage of installed capacity of photovoltaic plants is about 2,05%, and the electricity production in gross is 0,78%, which is quite low compared to other countries.

CHAPTER III. Methodology for researching the potential of solar radiation for the production of electrical energy in the Republic of North Macedonia

3.1. Methodology for researching the potential of solar radiation for the production of electrical energy from a photovoltaic power plant

In order to calculate the solar radiation potential for such systems, it is essential to apply an adequate research methodology. In this dissertation, a methodology is proposed, including the following stages:

a) Definition of location;

b) Collection of data on solar radiation;

c) Data Analysis;

d) Assessment of the potential for electricity production;

e) Interaction with the electrical network.

The study of the potential of solar radiation for the production of electrical energy from a photovoltaic power plant requires a systematic approach and the application of specialized methods and tools for analysis and modeling, the most effective being software using built-in climate databases [55, 56, 110 - 113, 126].

3.2. Selection of software for the study of the potential of solar radiation for the production of electrical energy

Various software tools have been studied which can be used to study the potential of solar radiation for the production of electrical energy from a PV power plant such as PVWatts, SolarGIS, Meteonorm, PVGIS. These software tools offer various possibilities for analyzing the potential of solar radiation for the production of electrical energy from photovoltaic power plants and can be useful for engineers designing photovoltaic systems and other professionals in the field of renewable energies.

For the research in the dissertation, due to the climatic database suitable for the PCM region with free access and the possibility to use a Web-based interface, the PVGIS software tool was chosen.

3.3. Selection of software for the design and simulation of the operation of photovoltaic systems

Various software products, that can be used for detailed design and simulation of the operation of photovoltaic systems, have been studied: PVsyst, SAM (System Advisor Model), HelioScope, RETScreen.

These software tools offer various possibilities for analyzing the potential of solar radiation for the production of electrical energy from photovoltaic power plants and can be useful for engineers, designers of photovoltaic systems, and other specialists in the field of renewable energies.

The most suitable functionality and database of FEC components available in RNM for the purposes of design and simulations in this dissertation is PVsyst, which is one of the professional software products for design and simulation of the operation of photovoltaic systems by electrical designers in Bulgaria.

3.4. Conclusions to Chapter Three

A methodology has been proposed for the study of the potential for the production of electrical energy from photovoltaic power plants and their modeling and simulation of the work. The software products PVGIS and PVsyst have been selected for the implementation of the methodology, presenting their capabilities and functions, from the application of which the following can be concluded:

1. The online PVGIS tool is convenient and free to use. Facilitates the way to perform a preliminary analysis of photovoltaic power plant projects by providing a database of the level of solar radiation and other meteorological and topographical indicators that are necessary to assess the potential for electrical energy production in a given geographic location.

2. PVGIS provides information on solar radiation in all parts of the world, including the territory of the Republic of North Macedonia, by calculating the expected electricity production, and through

it the expected electricity production can be simulated for daily, monthly and annual level. The display of results can be visually graphical and tabular.

3. The two software products provide a choice for the application of photovoltaic panels with different technologies, and in PVsyst there is an up-to-date database with detailed technical data of specific models of photovoltaic modules of a large number of manufacturers available on the market.

4. Provide the possibility of calculations for different panel placement angles as well as different orientation location. In this way, optimal calculations can be made for the production of electricity from photovoltaic plants for the specific location.

5. It is possible to carry out technical and economic calculations to assess the profitability of investments for the construction of the photovoltaic power plant.

CHAPTER IV. Simulation studies and analyzes in the design and implementation of new photovoltaic power plants - PhPP Oslomei-2 and PhPP Bitola

4.1. General and problem status

The Republic of North Macedonia is one of the warmest countries in the Balkans. Fig. 4.1 shows a map of the average annual solar for the Republic of North Macedonia, expressed in kWh/m^2/year. According to SOLARGIS data from 2019, solar radiation ranges from 1 241 kWh/m2 to 1 607 kWh/m^2. [120]

The subject of the doctoral dissertation is the implementation of simulation studies of the construction of two new photovoltaic power plants PhPP Oslomej 2.20 MW and PhPP Bitola 40 MW. PhPP Oslomei – 2, will be built in the Kichevo’s Valley in the north-eastern part of Kichevo, near the Oslomei TPP. Meanwhile, the PhPP Bitola will be built in the southwestern part of the country in the Pelagonian plain, 12 km southeast of the city of Bitola and in close proximity to the TPP Bitola [38], [39].

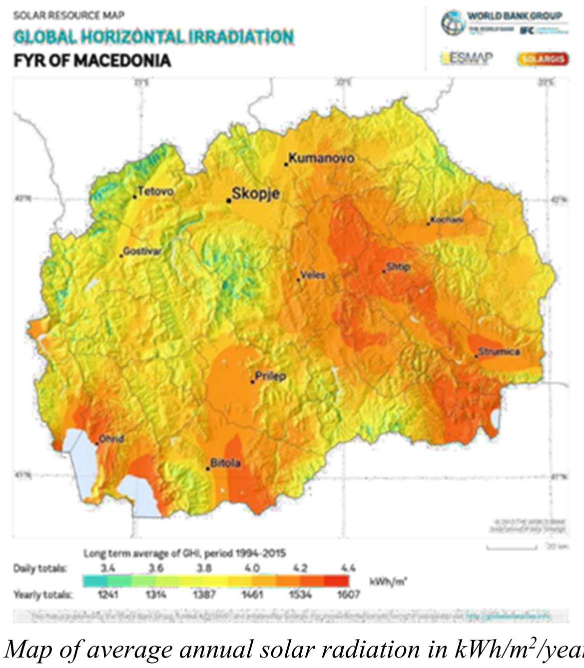


Figure 4.1. Map of average annual solar radiation in kWh/m^2/year. for PCM.

4.2. Prerequisites for reducing carbon dioxide emissions

With the construction of PhPP Bitola and PhPP Oslomei - 2, good foundations will be laid for the realization of the state's development goals in the field of sustainable development and the reduction of greenhouse gases in the atmosphere. [23], [26], [99]

To determine the exact CO_2 emission that would be created if coal, natural gas or photovoltaic panels were used to produce electricity, a calculation of the annual reduced amounts of CO_2 emissions was made. [27], [35]

Table 4.1voided carbon dioxide emissions when using photovoltaic panels

	Annual average production of energy	Emission factor	Annual carbon emissions dioxide	Emission (25 years)
	(KWh)	($kgCO_2$/KWh)	($kgCO_2$)	($kgCO_2$)
Coal	1 383,47	0,976	1 350,26	33 756
Natural gas	1 383,47	0,395	546,47	13 661
PhPP	1 383,47	0,351	485,597	12 140

With this comparison, it can be concluded that the production of electricity from photovoltaic panels has a positive impact on the environment and their use indirectly reduces greenhouse gas emissions. Applying a FEP with an average annual electricity production of 1 383,47 KWh for 25 years, the CO_2 emissions will amount to 12 140 kgCO2, and if using coal-fired thermal power plants with the same average annual electricity production, the CO_2 emissions for 25 years will be in the amount of 33 759 $kgCO_2$, which means that with the application of PhPP, CO_2 emissions decrease 2.78 times [22,84].

4.3. Study and simulation studies on solar radiation and expected production of the PhPP Bitola

The place where the construction of the PhPP Bitola is planned is in the immediate vicinity of the TPP Bitola, after KP 221/1 cadastral municipality Dobromiri in the municipality of Bitola. From the cadastral plot there is. area of 400,000 m^2, of which 400 000 m^2 will be used for the construction of the PhPP Bitola with an installed capacity of 40 MW (fig. 4.2). For electricity production, it is subject to high solar radiation with an average annual solar radiation energy density of 1 792 kWh/m2 (Fig. 4.3).[A4] ,[128, 132].

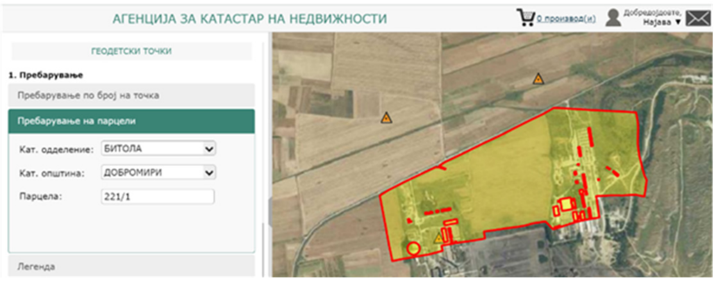


Figure4.2. Planned location of PhPP Bitola

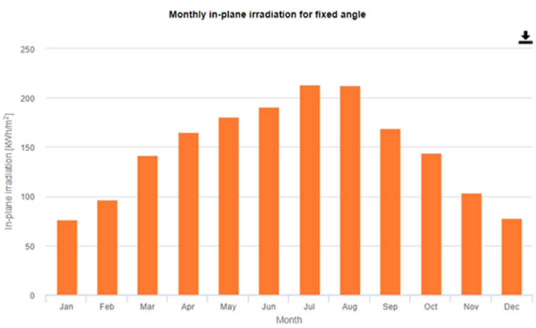


Figure 4.3. Average monthly values of the solar radiation falling on the photovoltaic modules installed at an optimal angle for the PhPPBitola, kWh/m²

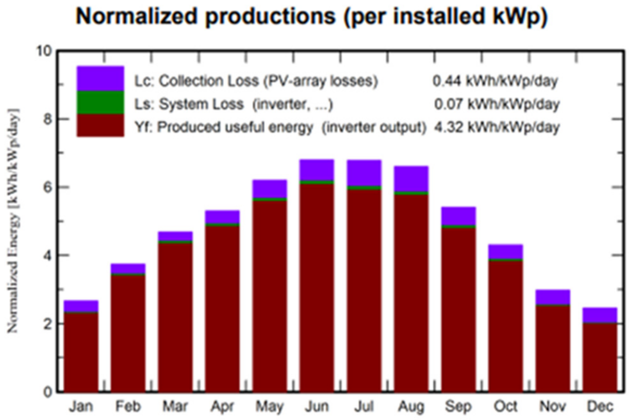


Figure 4.3. Estimated amount of electricity produced for a given system, with a fixed angle, kWh.

Figure 4.4. Appearance and location of the distribution substations at the PhPP Bitola

4.4. Compilation of a preliminary technical project of the PhPP Bitola

The PhPP Bitola is located near the villages of Dobromiri and Novatsi, southeast of Bitola, in the immediate vicinity of the TPP Bitola at KP 221/1.

A total of 73 216 photovoltaic modules with monocrystalline bifacial technology manufacturer type JETION type JT545SSh(B), with panel dimensions 2279x1134x30 mm and a peak power of 1 module 545 Wp. 176 inverter type SUN2000 -185 KTL – H1 are also planned. [86-92, 116, 135].

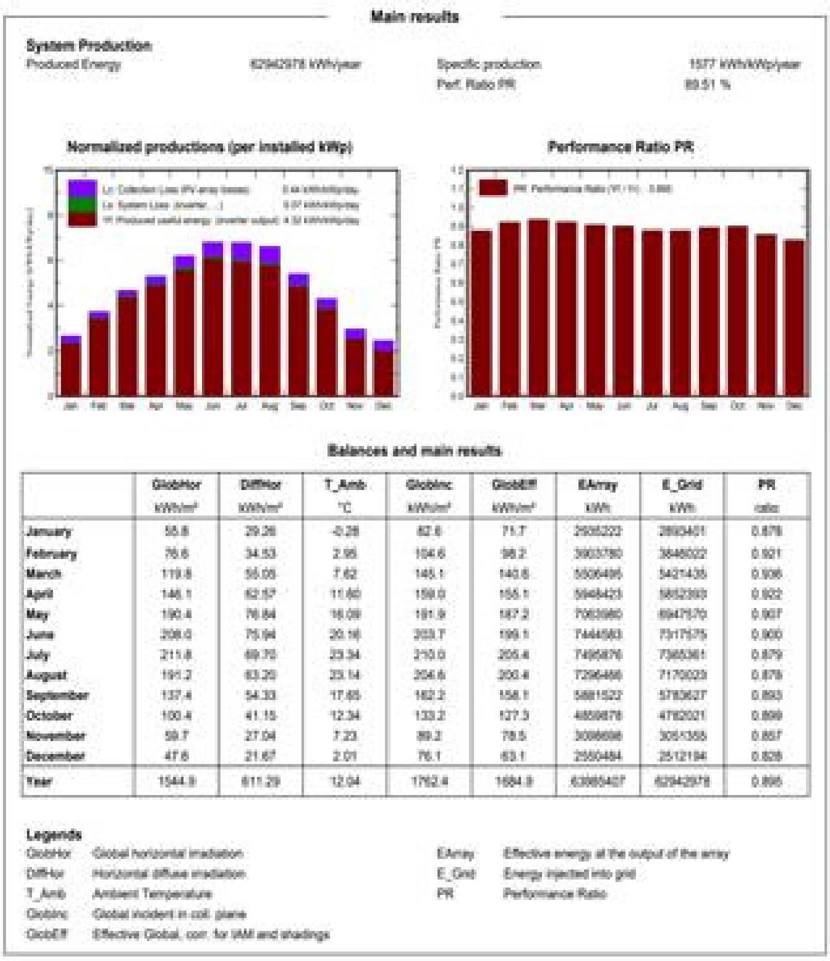
The installed capacity of PV Bitola will amount to 39,90 kWp, i.e. about 40 MW. The main components (described in detail in the dissertation) of PhPP Bitola are:

- Bearing structure made of hot-dip galvanized steel, fixed in the ground;
- Monocrystalline double-sided panels;
- DC/AC converters (photovoltaic inverters);
- Connecting DC cables;
- Connecting AC cables;
- Substations.

4.5. Simulation studies of the PhPP Bitola using PVsyst

Using the PVsyst software, several simulations have been made to select the most favorable one, which, with the correct equipment selection, will achieve the highest electricity production and efficiency at the main occupancy of the PV plant.

Shown in figures are the summarized and most important parameters for the photovoltaic power plant. Location Gorno Aldanci with coordinates 41.06 N; 21.49E. Panel angles are 25° and -12°. The number of modules is 73 216 and the installed capacity is 39,9 MW. Also shown are the specific electricity production as well as the expected electricity production.


Main results

System Production
Produced Energy 62942978 kWh/year
Specific production 1577 kWh/kWp/year
Perf. Ratio PR 89.51 %

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	55.8	29.26	-0.28	82.6	71.7	2935222	2893401	0.878
February	76.6	34.53	2.95	104.6	98.2	3903780	3846022	0.921
March	119.8	55.05	7.62	145.1	140.6	5506495	5421435	0.936
April	146.1	62.57	11.60	159.0	155.1	5948423	5852393	0.922
May	190.4	76.84	16.09	191.9	187.2	7063980	6947570	0.907
June	208.0	75.94	20.16	203.7	199.1	7444583	7317575	0.900
July	211.8	69.70	23.34	210.0	205.4	7495876	7365361	0.879
August	191.2	63.20	23.14	204.6	200.4	7296466	7170023	0.878
September	137.4	54.33	17.65	162.2	158.1	5881522	5783627	0.893
October	100.4	41.15	12.34	133.2	127.3	4859878	4782021	0.899
November	59.7	27.04	7.23	89.2	78.5	3098698	3051355	0.857
December	47.6	21.67	2.01	76.1	63.1	2550484	2512194	0.828
Year	1544.9	611.29	12.04	1762.4	1684.9	63985407	62942978	0.895

Legends
GlobHor Global horizontal irradiation
DiffHor Horizontal diffuse irradiation
T_Amb Ambient Temperature
GlobInc Global incident in coll. plane
GlobEff Effective Global, corr. for IAM and shadings
EArray Effective energy at the output of the array
E_Grid Energy injected into grid
PR Performance Ratio

Figure 4.17. Specific energy – ***Version 1***

Figure 4.17 shows that the specific energy [kWh/kWp] is a production indicator based on the available irradiance (location and orientation) on a monthly basis depending on temperature and location, and the energy losses that occur are minimal in practice.

Figure 4.18 shows the gross and net electricity that will be produced, as well as the losses that are generated by the inverters' own losses, cable losses, temperature, etc. The graph shows how much electricity comes out of the inverters and is injected into the grid.

Figure 4.19 shows the input-output diagram of the generated electricity during the day, as well as the injection of the generated electricity into the electricity network (electricity distribution/electricity transmission).

Figure 4.21 shows a graphical representation of the position of the photovoltaic panels relative to the sun, as well as the geographical location of the panels, i.e. the azimuth angle.

Figure 4.22 shows a tabular representation of panel shading during the day. From the inspection, it can be concluded that the placement is well chosen, since only a small part of the panels have a shadow from the neighboring panels.

Figure 4.23 shows the surface layer of photovoltaic panels that are not double-sided. Based on it, it is noted that they occupy a larger area compared to double-sided panels.

Figure 4.20 shows the grouping of modules into strings and series.

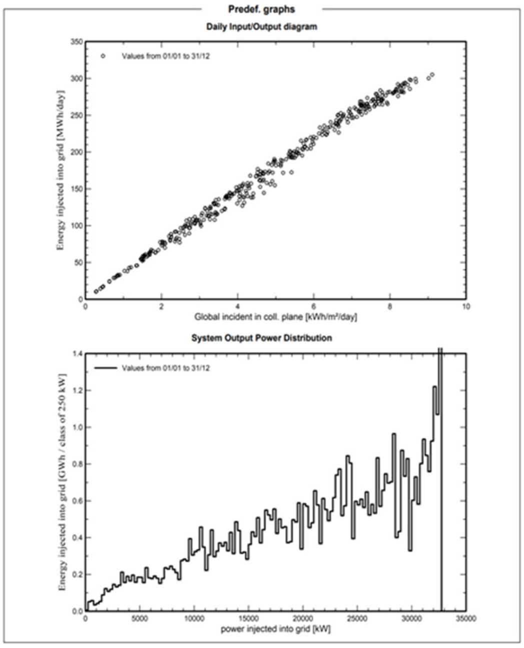


Figure 4.19. Cumulative electrical energy for Option 1

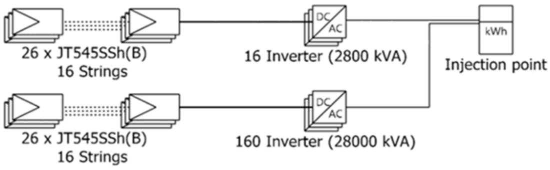


Figure 4.20. Scheme of connecting modules in strings and series

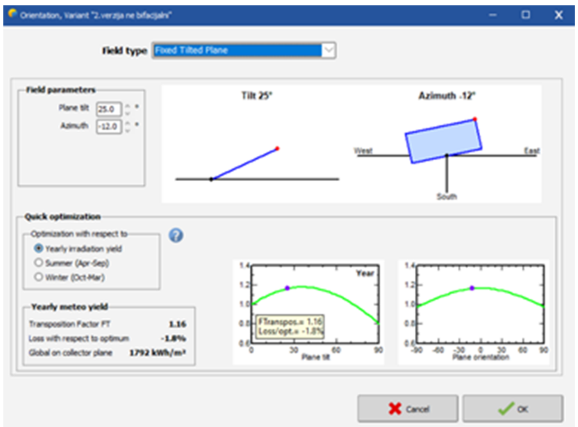
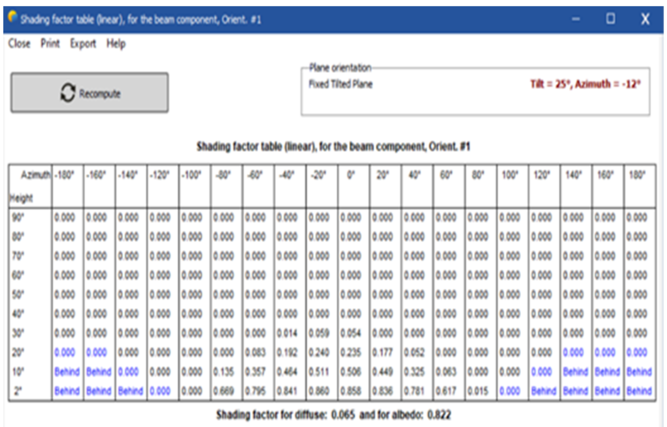


Figure 4.21 Tilt angle and azimuth of the PV modules


Shading factor table (linear), for the beam component, Orient. #1

Close Print Export Help

Recompute

Plane orientation: Fixed Tilted Plane — Tilt = 25°, Azimuth = -12°

Shading factor table (linear), for the beam component, Orient. #1

Azimuth / Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
70°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
60°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.059	0.054	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20°	0.000	0.000	0.000	0.000	0.000	0.000	0.083	0.192	0.240	0.235	0.177	0.052	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10°	Behind	Behind	0.000	0.000	0.000	0.135	0.357	0.464	0.511	0.506	0.449	0.325	0.063	0.000	0.000	0.000	Behind	Behind	Behind
2°	Behind	Behind	Behind	0.000	0.000	0.669	0.795	0.841	0.860	0.858	0.836	0.781	0.617	0.015	0.000	Behind	Behind	Behind	Behind

Shading factor for diffuse: 0.065 and for albedo: 0.822

Figure 4.22. Shading of PV modules

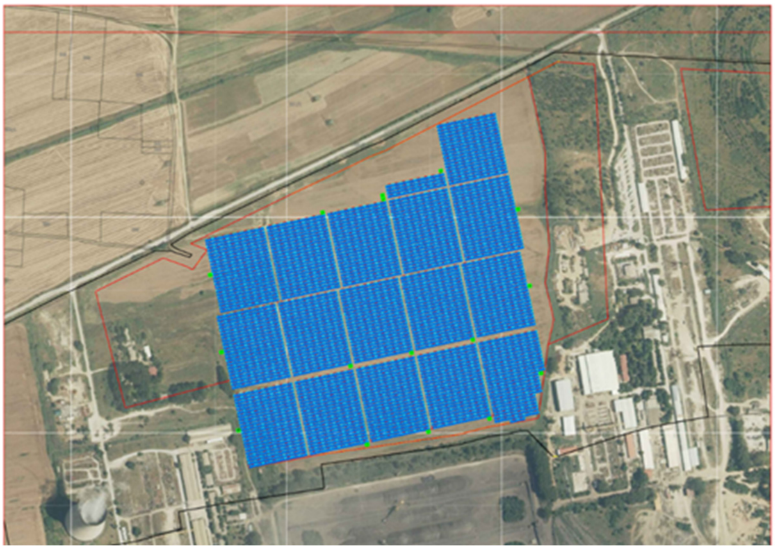


Figure 4.23. Layout of the panels on the site and location of TS of the PhPP Bitola

4.6. Comparative analysis of PhPP Bitola with different types of photovoltaic modules

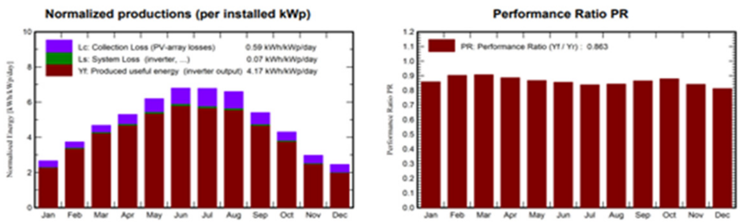
During the preparation of the PhD thesis, several measurements and analyzes were made at PVsyst to find the most favorable type of low-voltage panels that produce the largest amount of electricity per year. The optimality of the building surface is taken into account. An analysis was made, if the PhPP Bitola with the same or similar power is planned, which types of panels are most favorable. Cost was also considered when selecting PV panels, simulations and calculations were done with silicon and thin-film cadmium telluride PV panels (CdTe). [30], [58], [64], [66].

Main results

System Production

Produced Energy 62936051 kWh/year — Specific production 1522 kWh/kWp/year

Perf. Ratio PR 86.34 %



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	55.8	29.26	-0.28	82.6	71.7	2976550	2934073	0.859
February	76.6	34.53	2.95	104.6	98.2	3962799	3904176	0.902
March	119.8	55.05	7.62	145.1	140.5	5527945	5442420	0.907
April	146.1	62.57	11.60	159.0	154.8	5928852	5832726	0.887
May	190.4	76.84	16.09	191.9	186.8	6996115	6880486	0.867
June	208.0	75.94	20.16	203.7	198.6	7336841	7211370	0.856
July	211.8	69.70	23.34	210.0	205.0	7413299	7283727	0.838
August	191.2	63.20	23.14	204.6	200.1	7268442	7142408	0.844
September	137.4	54.33	17.65	162.2	157.9	5901233	5802971	0.865
October	100.4	41.15	12.34	133.2	127.3	4921505	4842643	0.879
November	59.7	27.04	7.23	89.2	78.5	3152849	3104237	0.841
December	47.6	21.67	2.01	76.1	63.1	2594256	2554816	0.812
Year	1544.9	611.29	12.04	1762.4	1682.4	63980685	62936051	0.863

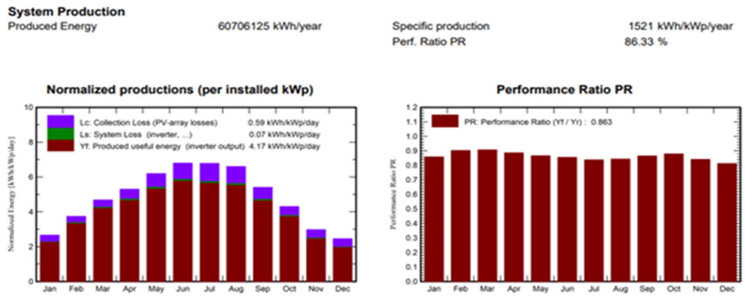
Legends

GlobHor Global horizontal irradiation
DiffHor Horizontal diffuse irradiation
T_Amb Ambient Temperature
GlobInc Global incident in coll. plane
GlobEff Effective Global, corr. for IAM and shadings
EArray Effective energy at the output of the array
E_Grid Energy injected into grid
PR Performance Ratio

*Figure 4.32. The specific energy – **Version 2***

In the dissertation, a **second version** of calculations was made with non-double-sided silicon modules from the same manufacturer, with the same power JT545SSh(B), double-layering in the calculations is excluded. The bearing angle and the azimuth are the same, i.e. 25^0 and -12^0. 75 894 panels are planned. The power according to the panels is 41,36 MW. 183 inverters of the SUN2000-185KTL-H1 type are planned, the total power according to the inverters is 32,02 MW. 2 919 with 26 modules connected in series are provided. In this case, the same produced electricity was obtained on an annual

basis, 62 936 051 kWh/year, 62 936 MWh/year. In the first option, the electricity produced was reduced by 6 928 kWh/year, that is, by 6,7 MWh/year. If we take into account the fact that more inverters are provided for 6 than the first variant with double-sided modules, this means that the cost of the entire investment will be higher, and the generated current is almost the same.[43]
In order for non-double-sided panels to produce the same amount of electricity, 103 more strings are needed on 26 panels, i.e. 2 678 more panels and 7 more inverters. Figure 4.32 shows that the specific energy [kWh/kWp] is a production indicator based on the available irradiance (location and orientation) on a monthly basis depending on temperature and location, as well as the energy losses that occur. The graph shows that the losses are minimal.



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	55.8	29.26	-0.28	82.6	71.7	2871207	2830241	0.859
February	76.6	34.53	2.95	104.6	98.2	3822467	3765926	0.902
March	119.8	55.05	7.62	145.1	140.4	5332438	5249935	0.907
April	146.1	62.57	11.60	159.0	154.8	5718383	5625694	0.887
May	190.4	76.84	16.09	191.9	186.8	6747408	6635909	0.867
June	208.0	75.94	20.16	203.7	198.6	7077020	6955993	0.856
July	211.8	69.70	23.34	210.0	205.0	7150361	7025403	0.838
August	191.2	63.20	23.14	204.6	200.1	7011046	6889472	0.844
September	137.4	54.33	17.65	162.2	157.9	5692130	5597353	0.865
October	100.4	41.15	12.34	133.2	127.2	4747561	4671478	0.879
November	59.7	27.04	7.23	89.2	78.5	3041303	2994416	0.841
December	47.6	21.67	2.01	76.1	63.1	2502338	2464307	0.812
Year	1544.9	611.29	12.04	1762.4	1682.3	61713660	60706125	0.863

Legends
GlobHor Global horizontal irradiation
DiffHor Horizontal diffuse irradiation
T_Amb Ambient Temperature
GlobInc Global incident in coll. plane
GlobEff Effective Global, corr. for IAM and shadings
EArray Effective energy at the output of the array
E_Grid Energy injected into grid
PR Performance Ratio

*Figure 4.41. Specific energy – **Version 3***

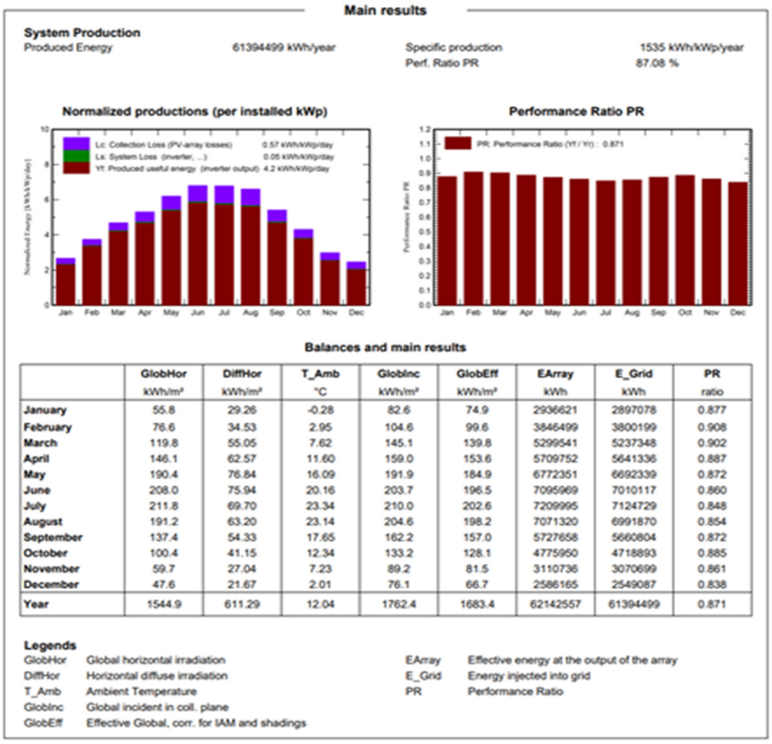
In the dissertation, a third variant of calculations and simulation was made with non-bilateral silicon modules from the same manufacturer, with the same power JT545SSh(B), the bifaciality in the calculations is turned off. The bearing angle and the azimuth are the same, i.e. 25^0 and -12^0. 73 216 panels are planned. The power according to the panels is 39,90 MW. 176 inverters of the SUN2000-185KTL-H1 type are planned, the total power of the inverters is 30,80 MW. There are 2 816 strings with 26 modules connected in series. In this case, less produced electricity was obtained on an annual basis 60 706 125 kWh/year, 60 706 MWh/year, 62 942 978 kWh/year, 62 943 MWh/year. From this calculation, it can be concluded that with the same number of panels but not bilateral with the same number of inverters, the electricity produced is lower by 2 236 853 kWh/year, 2 237 MWh/year.

The power of the photovoltaic plant is identical to that of the PhPP Bitola 39,9 MW.

Figure 4.41 shows that the specific energy [kWh/kWp] is a production indicator based on the available irradiance (location and orientation) on a monthly basis depending on temperature and location, as well as the energy losses that occur. The graph shows that the losses are minimal.

In the dissertation, a **fourth variant** of calculations was made with cadmium modules FS-6480A-C April2021, with a power of 480 Wp. The bearing angle and the azimuth are the same, i.e. 25^0 and -12^0. 83 340 panels are planned. The power according to panels is 40 MW. 160 GW25K-HT type inverters with 250 kW inverter power are planned, the total inverter power is 40 MW. 16 668 strings are provided with 5 modules connected in series. In this case, less produced electricity was obtained on an annual basis 61 394 499 kWh/year, 61 394 MWh/year, compared to the double-sided panels of the first option 62 942 978 kWh/year, 62 943 MWh/year. From this calculation, it can be concluded that the number of panels has significantly increased compared to the two-sided ones by 10 124, also the number of inverters has decreased by 16, the electricity produced is lower by 1 548 479 kWh/year, 1 548 MWh/year.[52]

The power of the photovoltaic plant has been significantly increased compared to the first variant with the bilateral modules of the PhPP Bitola 39,90 MW.



	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	55.8	29.26	-0.28	82.6	74.9	2936621	2897078	0.877
February	76.6	34.53	2.95	104.6	99.6	3846499	3800199	0.908
March	119.8	55.05	7.62	145.1	139.8	5299541	5237348	0.902
April	146.1	62.57	11.60	159.0	153.6	5709752	5641336	0.887
May	190.4	76.84	16.09	191.9	184.9	6772351	6692339	0.872
June	208.0	75.94	20.16	203.7	196.5	7095969	7010117	0.860
July	211.8	69.70	23.34	210.0	202.6	7209995	7124729	0.848
August	191.2	63.20	23.14	204.6	198.2	7071320	6991870	0.854
September	137.4	54.33	17.65	162.2	157.0	5727658	5660804	0.872
October	100.4	41.15	12.34	133.2	128.1	4775950	4718893	0.885
November	59.7	27.04	7.23	89.2	81.5	3110736	3070699	0.861
December	47.6	21.67	2.01	76.1	66.7	2586165	2549087	0.838
Year	1544.9	611.29	12.04	1762.4	1683.4	62142557	61394499	0.871

Figure 4.50. Specific energy– ***Varijant 4***

Figure 4.50 shows that the specific energy [kWh/kWp] is a production indicator based on the available irradiance (location and orientation) on a monthly basis depending on temperature and location, as well as the energy losses that occur. The graph shows that the losses are minimal.

4.7. Simulation studies of the PhPP Oslomej-2

It is planned to build PhPP Oslomej -2 in the immediate vicinity of TPP Oslomej, on several cadastral plots in the municipality of Shutovo, cadastral municipality KP 2459/1, Serbitsa von Grad, municipality of Kichevo (fig. 4.54). On the selected cadastral plot, the construction of the PhPP Oslomei-2 power plant with an installed capacity of 20 MW on an area of about 200,000 m2 is planned. For electricity production, it is exposed to solar radiation with an average annual solar radiation energy density of 1 539 kWh/m2.[A5]

The PVsyst database was used to calculate and simulate the production of electricity from the photovoltaic panels that will be placed on part of the facilities owned by PhPP Oslomej -2 (Fig. 4.55).

The location of the object is with coordinates: N: 41.58, E: 21.01

Some of the common values are shown below:

- Nominal power of installed photovoltaic panels: 19 950 kW (crystalline silicon double-sided photovoltaic panels),
- Specific production of electrical energy 1 395 kWh/kWp/year
- Expected annual electricity production of 27 823 MWh
- Mounting angle of the photovoltaic panels: 10^0
- Azimuth of installation of photovoltaic panels: -90^0, 90^0

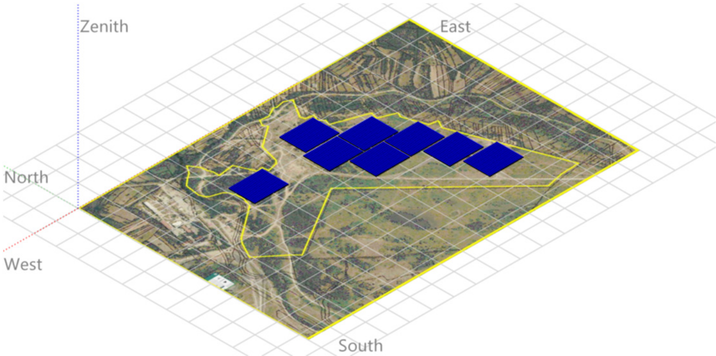


Figure 4.54. Planned location for PhPP Oslomej - 2

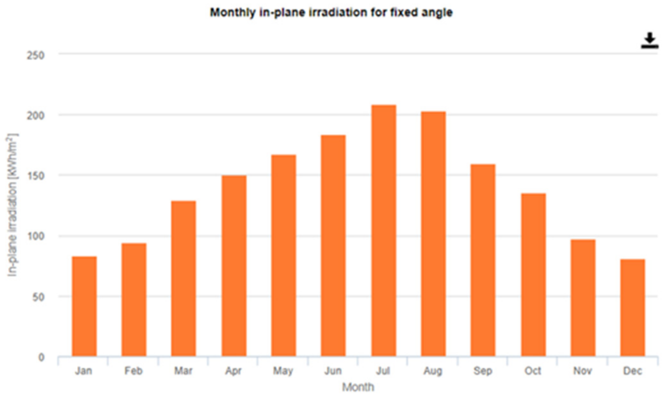


Figure 4.55. Average monthly levels of solar radiation for PhPP Oslomej - 2, kWh/m²

The installed capacity of the PhPP Oslomej – 2 will amount to 19,95 kWp, i.e. about 20 MW. The main components of the PhPP Oslomej - 2, described in detail in the dissertation, are:

- Bearing structure made of hot-dip galvanized steel, fixed in the ground;
- Monocrystalline double-sided panels;
- DC/AC photovoltaic inverters;
- DC and AC cables;
- Power substations.

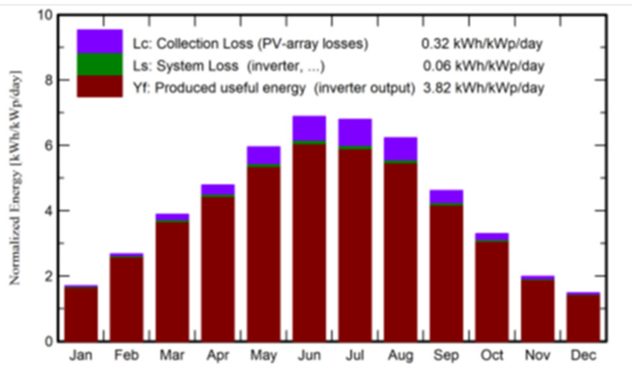


Figure 4.56. Estimated amount of electricity produced for PhPP Oslomej - 2, kWh

PhPP Oslomej - 2 is located near the village of Oslomei, southeast of Kichevo, in the immediate vicinity of TPP Oslomej at KP 2459/1. A total of 36,608 photovoltaic modules with monocrystalline bifacial technology, JETION type JT545SSh(B), with panel dimensions of 2279x1134x30 mm and peak module power of 545 Wp are planned to be installed at this site. 88 inverters are also planned, of which SUN2000 -185 KTL – H1. The installed capacity of PhPP Oslomej - 2 will be 19,95 kWp, i.e. 20 MW. Photovoltaic panels are placed to the sun at an angle of 10^0, half of the number of designed panels are placed at the same and the other half to the west with an azimuth of 90^0 and -90^0. Figures 4.57 and 4.58 show the arrangement of the panels, and in the following figs. Figures 4.59 and 4.60 present shading data.

Figures 4.61 and 4.62 show the location and orientation of the used modules.

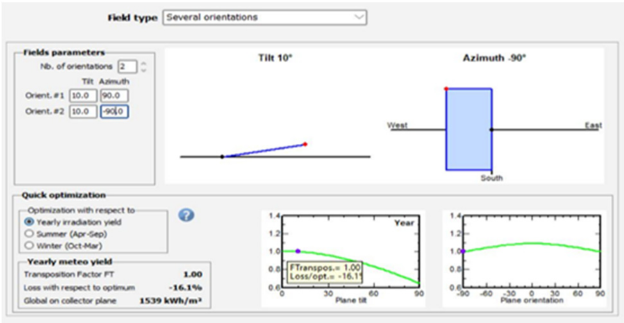


Figure 4.57. Installation diagram of photovoltaic panels oriented to the west

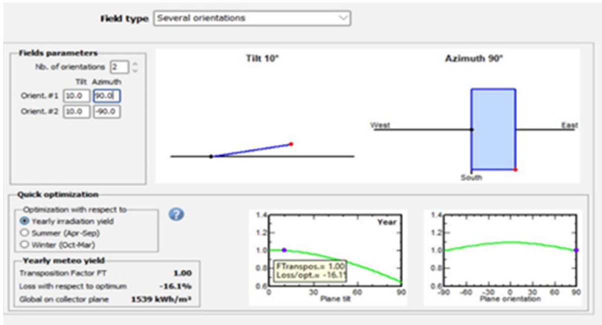
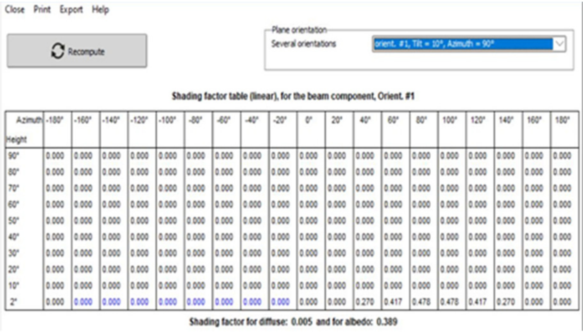


Figure 4.58 Installation diagram of photovoltaic panels oriented to the east

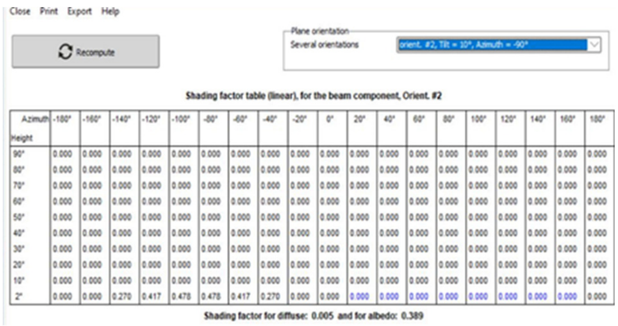


Shading factor table (linear), for the beam component, Orient. #1

Azimuth / Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
70°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
60°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.270	0.417	0.478	0.478	0.417	0.270	0.000	0.000

Shading factor for diffuse: 0.005 and for albedo: 0.389

Figure 4.59 Shading of photovoltaic panels facing west



Shading factor table (linear), for the beam component, Orient. #2

Azimuth / Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
70°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
60°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
50°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
40°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10°	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2°	0.000	0.000	0.270	0.417	0.478	0.478	0.417	0.270	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Shading factor for diffuse: 0.005 and for albedo: 0.389

Figure 4.60 Shading of photovoltaic panels facing east

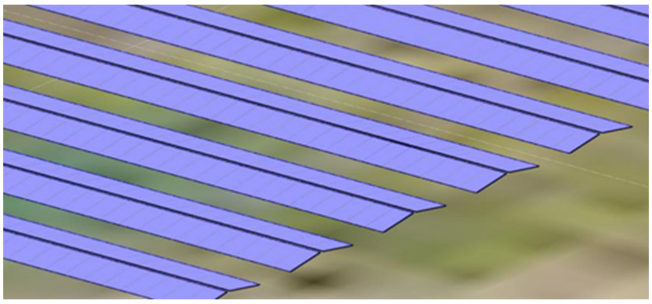


Figure 4.61. Orientation of photovoltaic panels east-west

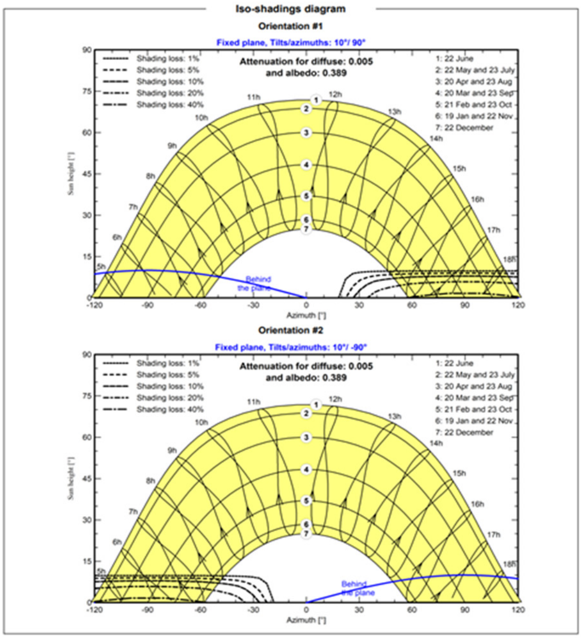
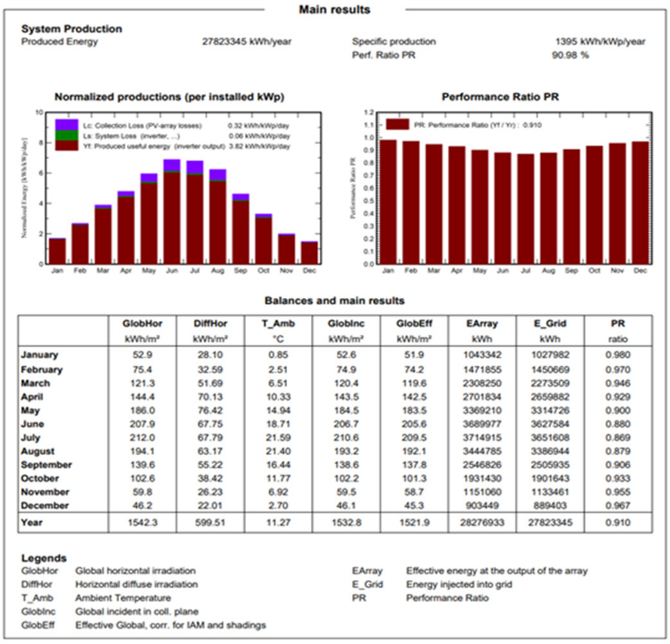


Figure 4.67. Scheme of shading of the panels during the day



	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	52.9	28.10	0.85	52.6	51.9	1043342	1027982	0.980
February	75.4	32.59	2.51	74.9	74.2	1471855	1450669	0.970
March	121.3	51.69	6.51	120.4	119.6	2308250	2273509	0.946
April	144.4	70.13	10.33	143.5	142.5	2701834	2659882	0.929
May	186.0	76.42	14.94	184.5	183.5	3369210	3314726	0.900
June	207.9	67.75	18.71	206.7	205.6	3689977	3627584	0.880
July	212.0	67.79	21.59	210.6	209.5	3714915	3651608	0.869
August	194.1	63.17	21.40	193.2	192.1	3444785	3386944	0.879
September	139.6	55.22	16.44	138.6	137.8	2546826	2505935	0.906
October	102.6	38.42	11.77	102.2	101.3	1931430	1901643	0.933
November	59.8	26.23	6.92	59.5	58.7	1151060	1133461	0.955
December	46.2	22.01	2.70	46.1	45.3	903449	889403	0.967
Year	1542.3	599.51	11.27	1532.8	1521.9	28276933	27823345	0.910

Figure 4.68. The specific energy

Figure 4.67 shows the mutual shading of the panels during the day from 5 am to 7 pm for different azimuth angle. Figure 4.68 shows that the specific energy [kWh/kWp] is a production indicator based on the available radiation (location and orientation) on a monthly basis depending on the temperature and location, as well as the energy losses that occur. The graph shows that the losses are minimal.

4.8. FEC Tele management

To increase their energy efficiency, mobile operators have started to build photovoltaic plants on the roofs of buildings to reduce their electricity costs, as well as on buildings where they have placed antennas for data transmission. In the Republic of North Macedonia, mobile network coverage is 90%. In certain mountainous areas, where there is no power distribution network or there is one, but the reliability of the power distribution network is not within the limits of the permitted technical norms, for these reasons the construction of photovoltaic plants for base stations or for antenna poles is frequent, in order to increase the reliability of the mobile net.[A1], [47]

In the vicinity of the PhPP Oslomej, 80 km to the southeast, a power plant - a Telecom base station with a capacity of 29.28 kW - is planned. There is no electricity distribution network built in this area, and its construction would be very expensive. 96 JAM60-DO3-BP type panels and one SUN2000-30KTL-M3-480V inverter are provided, as well as one 12v 200Ah electricity storage battery. There are 4 strings with 24 modules connected in series.

The installation angle is 25^0 and the azimuth -10^0, the surface of the panels is 160 m^2. The expected annual production of electricity is 44 340 kWh/year Figure 4.72. [133-134]

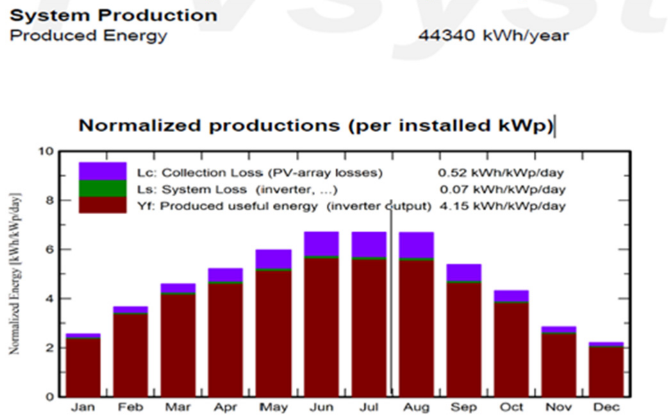


Figure 4.72. Expected annual production

Figure 4.73 shows the connection of strings and inverters, and figure 4.74 shows a view of the base station installed.

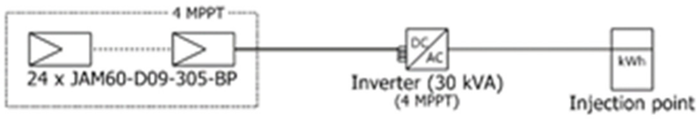


Figure 4.73. Scheme of connecting modules in strings and with inverters

Figure 4.74. Exterior of the base station

4.9. Simulation study of the effect of the construction of the two PhPP 60 MWp on the country's electricity mix: seasonal and annual

From the simulations made for PhPP Bitola 40 MW and PhPP Oslomej 2, 20 MW according to the software program PVsyst, it can be noted that in winter a total electricity production of 12 628 MWh is expected, in spring 26 469 MWh, in summer 32 522 MWh and in autumn 19 147 MWh. The total electricity produced will amount to 90 766 MWh (Table 4.9).

The total electricity produced in the Republic of North Macedonia in 2021 is 5 284 800 MWh, with the total expected electricity produced by PhPP Bitola 40 MW and PhPP Oslomej 2, 20 MW amounting to 5 375 566 MWh, representing an increase of 1,72%. Considering that these photovoltaic plants are planned to be built by JSC ESM, whose electricity production is 3 273 600 MWh, the total production of JSC ESM alone will be 3 364 366 MWh, which represents an increase of 2,78%.

JSC ESM In 2021, in the winter there is an illuminated electricity production of 1 145 760 MWh, in the spring 491 040 MWh, in the summer 654 720 MWh and in the autumn 982 080 MWh.

From the analysis, it can be concluded that JSC ESM, after the construction of the two PhPP, will have the highest percentage of the total electricity produced in spring with 5,34%, then in summer 4,87%, then in autumn 1,95% and finally in winter 1,10%. The largest percentage share of the new PhPPs is 5,34% of the total electricity production of JSC ESM in the spring.

The reason for this is that during this period the electricity produced is the lowest, considering that the total electricity consumption in spring is the least.

The electricity production in summer is second, as a result, the electricity generated will increase from the new PVs, and the electricity consumption is higher compared to the spring, because due to the high temperatures, the total electricity consumption increases due to the use of air conditioners for cooling, which are mainly used during the day.

Table 4.9. Produced electrical energy at the connection of the new PhPP Bitola and PhPP Oslomej

Season	PhPP Bitola 40 MW, production energy MWh	PhPP Oslomej - 2, 20 MW production energy MWh	Total MWh	Total electricity production of JSC ECM MWh	PhPP % of total electricity production of JSC ESM
winter	9 252	3 376	12 628	1 145 760	1,10%
spring	18 223	8 246	26 469	491 040	5,34%
summer	21 851	10 671	32 522	654 720	4,97%
autumn	13 617	5 530	19 147	983 080	1,95%
Total	62 943	27 823	90 766	3 273 600	2,78%

4.10. Conclusions to Chapter Four

In this chapter, parameter calculation and simulation study of two large-capacity photovoltaic plants – PhPP Bitola 40 MW and PhPP Oslomej 2.20 MW - are presented. Based on this, the following more important conclusions can be drawn:

1. The locations of the photovoltaic plants were chosen on land owned by JSC ESM, with the intention that the largest producer of electricity would build them in the shortest possible time, without legal obstacles to implementation.

2. The connections of PhPP Bitola 40 MW and PhPP Oslomej - 2, 20 MW are possible and realistic, considering the weak production of electricity in thermal power plants TPP Bitola and TPP Oslomej. Which means that there is capacity to connect the existing transformer stations in TC Bitola 2, 400/100 kV/kV and TC Oslomej 110/35 kV/kV. Currently, only one PhPP Bitola-Novatsi with an installed capacity of 50 MW has been built in 9-10 months, the investment of which is a foreign, Turkish private company. It was released under pressure on 29.10.2023. Another PhPP Oslomei has been built with an installed capacity of 50 MW, is connected to the electricity grid, but is in the equipment testing phase. The PhPP Oslomej 50 MW was built with a public-private partnership with a foreign Bulgarian company and JSC ESM, which participates with 30%. The PhPP has a temporary license until the equipment is tested, how it will affect the electricity grid, if there are any deficiencies, they must be fixed in the meantime until a permanent power generation license is obtained.

3. For the PhPP Bitola, a place was chosen where the solar radiation is high and amounts to 1 792 kWh/m2/year. The choice of location is made so that it does not represent a problem for realization. Given the proximity of the location to TS Bitola 2, 400/100 kV/kV, connection costs will be minimal. The expected annual production of electricity is 62 943 MWh.

4. For PhPP Oslomei - 2, a place was chosen where the solar radiation is high and amounts to 1 539 kWh/m2/year. The choice of location is made so that it does not represent a problem for implementation. Given the location's proximity to the TS Oslomej 110/35 kV/kV, connection costs will be minimal. The expected annual electricity production is 23 823 MWh.

5. The same type of equipment with the same technical characteristics for the photovoltaic modules and inverters is planned for the two photovoltaic plants, Jetion JT545SSh(B) was selected for photovoltaic panels, and SUN2000 -185 KTL – H1 Currently, this type of equipment is the most demanded in the market in Republic of North Macedonia, so their price is acceptable. Depending on the power, the number of photovoltaic panels and inverters is selected.

6. In selecting the locations, it was considered that the solar radiation would be high and therefore the expected production would be the highest. Photovoltaic plants must be close to an existing power transmission/distribution network where there are technical conditions for connection. All this would allow for the fastest construction, lowest investment costs and rapid deployment in the power system, injection of produced electricity, as well as an increase in total domestic electricity production.

7. Simulations were made with different types of photovoltaic panels, and based on the results, the equipment that gives the highest produced electricity for the specific case was selected.

8. From the point of view of the efficiency of the system, when choosing equipment, their price is taken into account as criteria and a balance between low price and good quality is chosen.

9. From the conducted simulations for the PhPP Oslomej, it has been proven that the east-west position gives the best results for the produced electricity and is therefore recommended when building and setting up the system.

CHAPTER V. Energy efficiency from the implementation of photovoltaic power plants in the electricity system of the Republic of North Macedonia

5.1. Models of energy flows of PhPP in the energy system of the Republic of North Macedonia

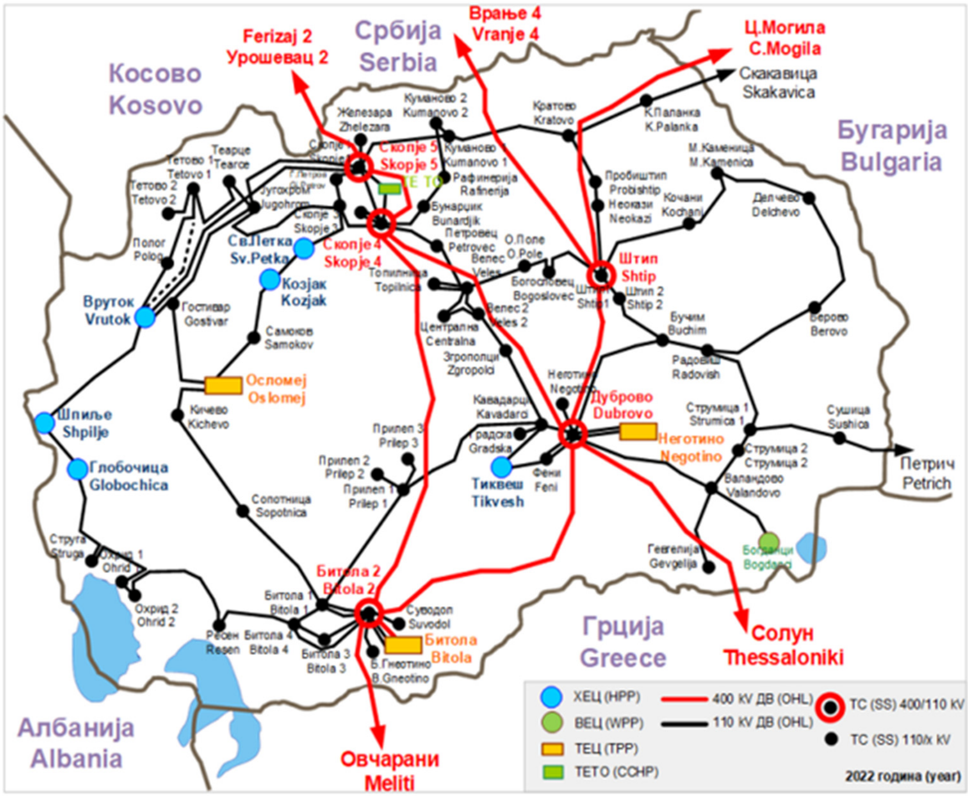


Figure 5.1. Topology of the electricity transmission network in 2022.

Modeling, monitoring and simulations of energy flows need to be performed using specialized software compatible with the software of the RNM power transmission operator. With it, simulations and calculations were carried out for the possibility of implementing new production facilities. The simulations of the connections of the newly planned PhPP were done using PSS (Power System Simulation and Modeling) Siemens.

Figure 5.1 shows the topology of the power transmission network in RNM. The power transmission network in the Republic of Macedonia consists of 400 kV and 110 kV transmission lines.

The Republic of North Macedonia is connected with the neighboring countries, namely with the Republic of Greece, it builds transmission lines, namely the 400 kV transmission line TS Bitola 2, 400/110 kV/kV - Megiti and the 400 kV transmission line TS Dubrovo 2, 400/110 kV/kV - Thessaloniki, with the Republic of Bulgaria with the transmission line TS Stip 400/110 kV/kV– Crvena Mogila, with R. Serbia 400 kV transmission line Substation TS Stip 400/110 - Vranje 4 and with Kosovo with 400 kV transmission line TS Skopje 5, 400/110 kV/kV - Urosevac (Ferizaj 2). Also in the central part of the district Macedonia also gravitates towards a voltage level of 400 kV, namely the 400 kV transmission line TS Bitola 2 - TS Skopje 4, TS Skopje 4 - TS Skopje 5, TS Bitola 2 - TS Dubrovo, TS Dubrovo - TS Skopje 4 and TS Dubrovo - TS Stip 1. The goal is the construction of corridor 7, which will be a 400 kV transmission line Bitola 2 - Elbasan R. Albania. This project also provides for the reconstruction of the TS Ohrid substation, which must switch to 400/110 kV/kV.

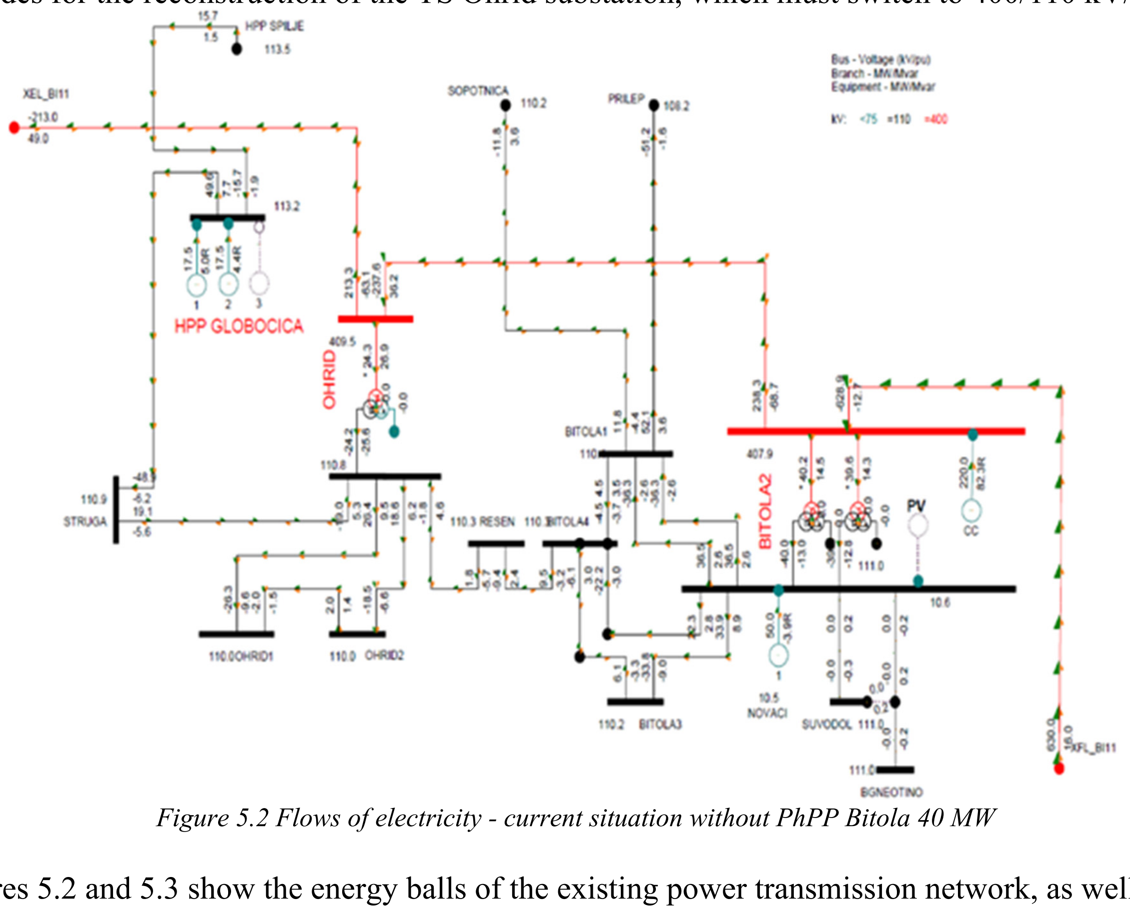


Figure 5.2 Flows of electricity - current situation without PhPP Bitola 40 MW

Figures 5.2 and 5.3 show the energy balls of the existing power transmission network, as well as the newly planned one with the construction of the PhPP Bitola. It can be seen from graph 5.2 in the TS 400/110 kV/kV Bitola 2 section that currently the Suvodol and Gneotino mines are not in operation, therefore there are no flows of electricity. In TS 400/110 kV/kV Bitola 2 there are three power transformers with a capacity of 230 MW each. This part is intended for the implementation of the green scenario of the Development Strategy of the Republic of North Macedonia.

Figure 5.3 shows that new production facilities are planned. At the voltage level of 110 kV in Bitola 2, one Novaci-MEJ FPP with an installed capacity of 50 MW is already connected, a new PhPP Bitola with an installed capacity of 40 MW is planned, which is covered by this article. A new cogeneration

plant with an installed capacity of 220 MW is also planned, which will produce both electricity and heat energy. If we look at the voltage conditions in TC Bitola 2 on the 110 kV bus, it can be noted that the voltage is within the permissible limits and is 111 kV. This means that PhPP Bitola 2, as well as the cogeneration plant, will not at all violate the technical parameters of the electricity transmission network, but on the contrary, will improve them, considering that two users of two cities in the Republic of North of Macedonia, Bitola and Prilep, which have a high consumption of electricity. Figures 5.2 and 5.3 also show the newly planned connection 400 kV Substation Bitola - Substation Ohrid - Elbasan R. Albania.
Figures 5.4 and 5.5 show the power currents in the power transmission network in the existing state and after the connection of the PhPP Bitola 40 MW and PhPP Oslomej 2, 20 MW. The figures showing the current state of the power in the power transmission network also show the newly built PhPP Novaci-MEJ and PhPP Oslomej OSN. From fig. 5.4 it can be seen that TS Oslomej110/35/10 kV/kV/kV has no load, mainly because the mine is not in operation, therefore the power flows are negligible. And in this region, the green scenario from the Development Strategy can be applied, that is, new power plants, especially photovoltaic ones, can be built at the expense of the non-working TPP Oslomej.
In Figure 5.5, a photovoltaic power plant PhPP Oslomei OSN, a private investment with an installed capacity of 50 MW, which has a license for trial operation, i.e. for testing the equipment, is already connected to TC Oslomej 110/35/10 kV/ kV/kV.

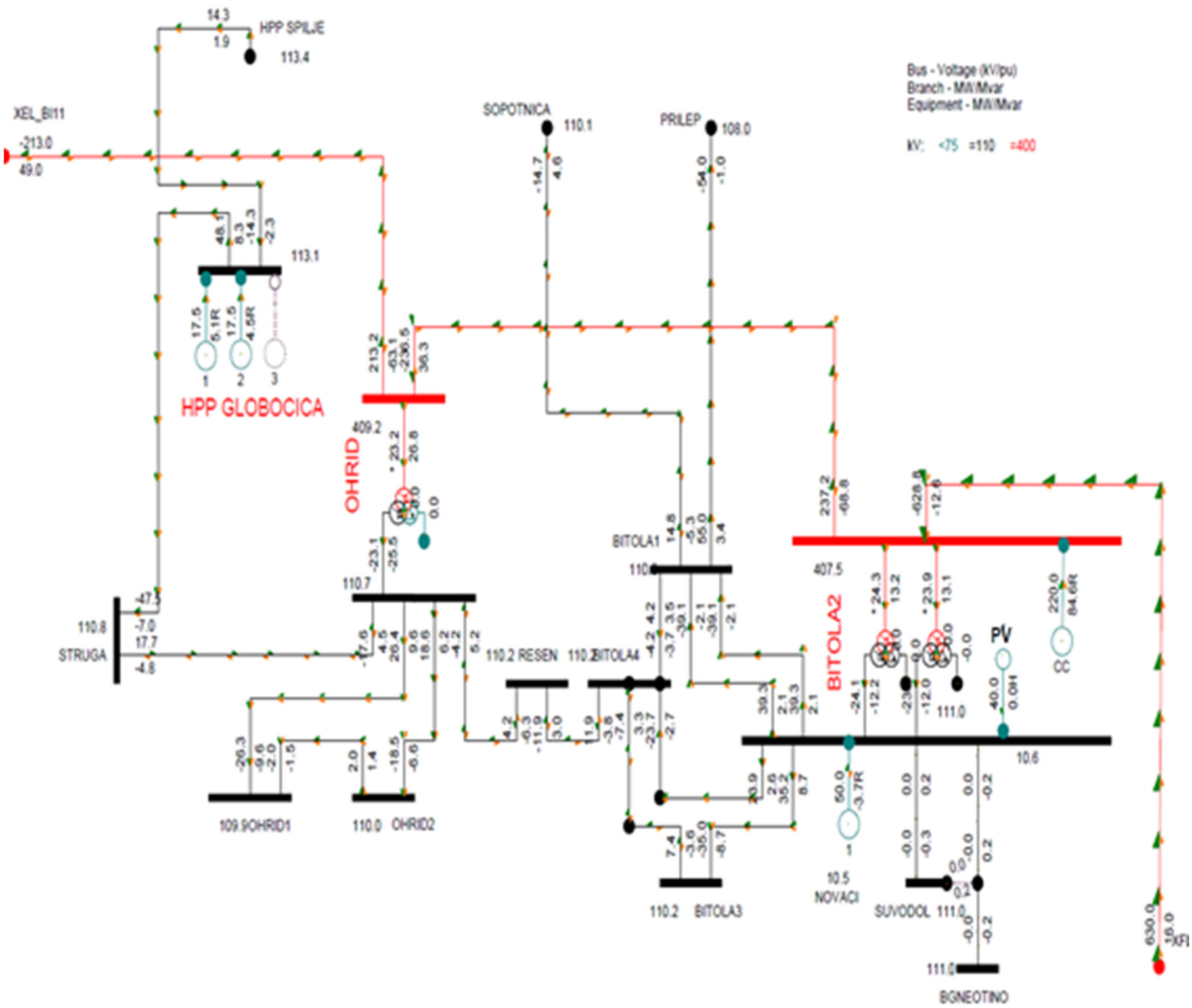


Figure 5.3 . Electricity flows - situation with new PhPP Bitola 40 MW

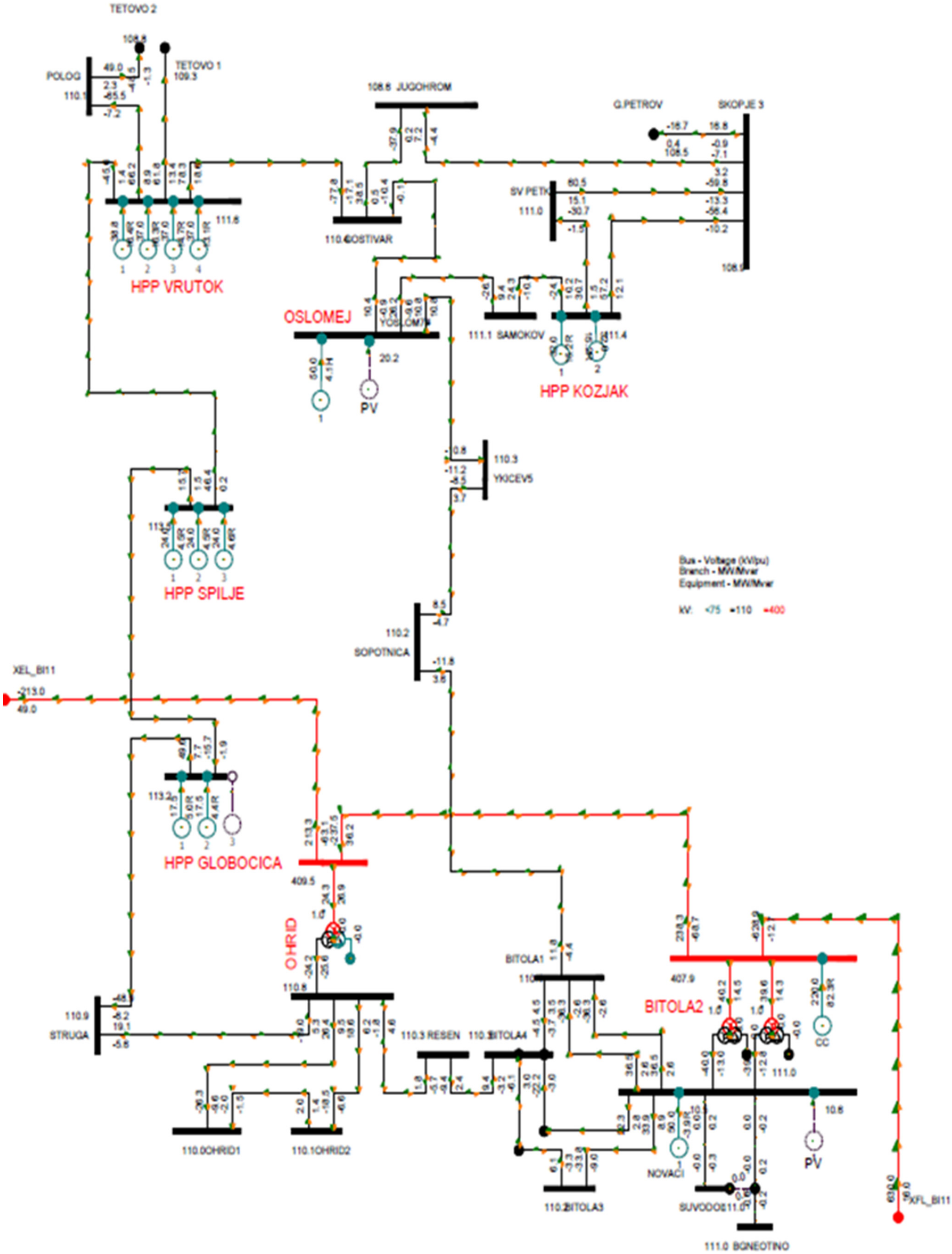


Figure 5.4 Electricity flows - current situation without the PhPP Oslomei 20 MW

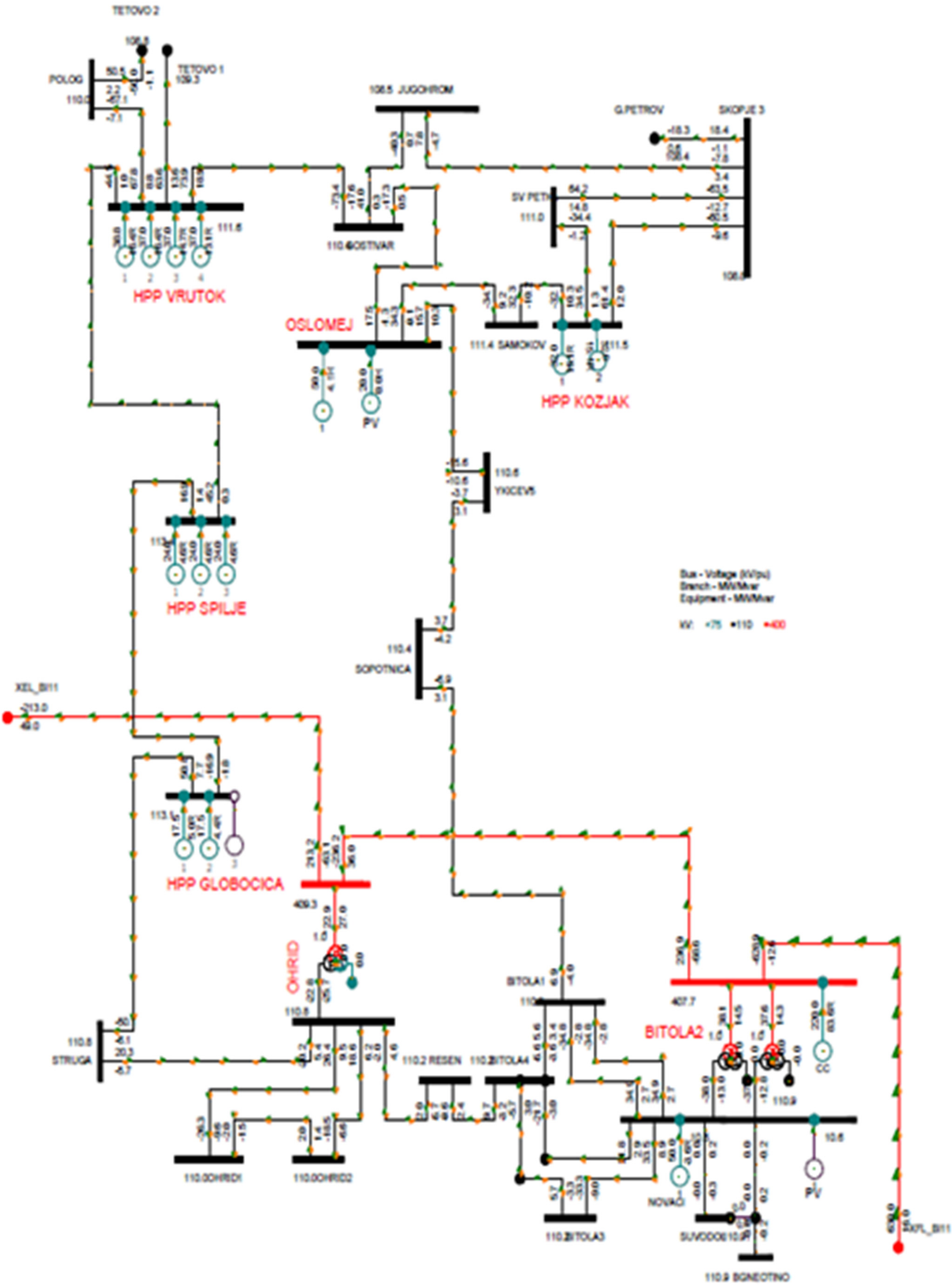


Figure 5.5. Electricity flows - current situation with new PhPP Oslomei 20 MW

5.2. Electromagnetic compatibility of a smart power grid

In the general case, there are standards regulating interaction between three systems: power network, electrical equipment and surrounding space (Fig. 5.6).

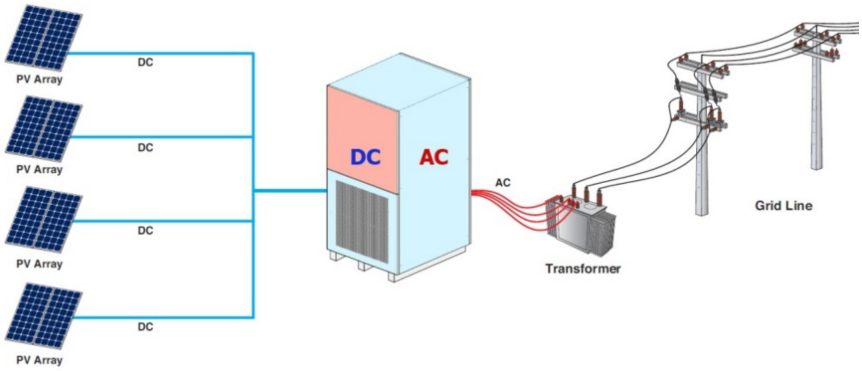


Figure 5.6. Example of „grid connected"of PhPP

The objectives of the standards related to the interaction between the supply network and the electrical equipment are the following: guaranteeing the operation of the electrical equipment connected to an electrical distribution network, limiting the level of harmful harmonics and interference, ensuring the ability to withstand a certain level of harmonics and interference and delivering electrical energy of a quality compatible with the characteristics of the equipment.

5.3. Preliminary assessment and costs for the inclusion of the PhPP Bitola in the electricity transmission network

In Appendix 1 in Table P.1, all activities, materials and other costs related to the construction and connection of the PhPP Bitola to the electricity transmission network of the Republic of N. Macedonia are presented.

The total cost of the construction of TS 110/10 kV/kV, 50 kVA, together with a 110 kV transmission line and a 10 kV distribution is 7 257 581 euros including VAT, and this is presented in Table P.3 (Appendix 3).

The value of the construction of the PhPP Bitola 40 MW is 23 103 563 euros including VAT.

The total value of the entire investment will amount to EUR 30 361 144 including VAT.

5.4. Preliminary assessment and costs for the inclusion of the PhPP Oslomej - 2 in the electricity transmission network

In Appendix 4 in Table P.4, I have presented all the activities, materials and other costs related to the construction and connection of the PhPP Oslomej - 2 power plant to the electricity transmission network of the Republic of S. Macedonia.

Total cost of the PhPP Oslomej - 2, 20 MW and 35 KV connection

The total value of the PhPP Oslomej 20 MW is 12,568,554 euros.

The cost of a 35 kV connection is 613,600 euros.

The total investment will amount to 13,182,154 euros

5.5. Technical and economic analysis of the investments of PhPP Bitola 40 MW and PhPP Oslomej - 2, MW

The total investment of PhPP Bitola 40 MW amounts to 30 361 144 euros including VAT. While the total investment of PhPP Oslomej -2, 20 MW amounts to EUR 13 182 154 including VAT. This means that the two investments together will amount to 43 543 298 euros including VAT.

The total expected annual electricity produced by PhPP Bitola 40 MW is 62 943 MWh. While the total expected annual electricity produced by the PhPP Oslomej - 2.40 MW is 27 823 MWh. The two photovoltaic power plants PhPP Bitola 40 MW and PhPP Oslomej - 2.40 MW will produce a total of 90 766 MWh. If it is taken into account that in 2021 the import of electricity amounts to 2 621 GWh, then with the construction of the newly planned photovoltaic plants, the import will decrease and amount to 2 539 438 MWh. With the construction of PhPP Bitola and PhPP Oslomej-2, the import of electricity will decrease by 3,46%.

Table 5.1. Expected monthly production

2024					2025			
month	MWh	euro/MWh	euro		month	MWh	euro/MWh	euro
Jenuary	4 940	200	988 000		Jenuary	4 940	200	988 000
February	4 034	200	806 800		February	4 034	200	806 800
March	7 780	150	1 167 000		March	7 780	150	1 167 000
April	7 800	150	1 170 000		April	7 800	150	1 170 000
May	9 736	150	1 460 400		May	9 736	150	1 460 400
June	9 736	150	1 460 400		June	9 736	150	1 460 400
July	9 736	150	1 460 400		July	9 736	150	1 460 400
August	9 736	150	1 460 400		August	9 736	150	1 460 400
September	9 736	150	1 460 400		September	9 736	150	1 460 400
Octomber	8 532	200	1 706 400		Octomber	8 532	200	1 706 400
November	4 500	200	900 000		November	4 500	200	900 000
December	4 500	200	900 000		December	4 500	200	900 000
	90 766		13 479 800			90 766		13 479 800

Таблица 5.2. Expected monthly production

2026					2027			
month	MWh	euro/MWh	euro		month	MWh	euro/MWh	euro
Jenuary	4 940	200	988 000		Jenuary	4 940	200	988 000
February	4 034	200	806 800		February	4 034	200	806 800
March	7 780	150	1 167 000		March	7 780	150	1 167 000
April	7 800	150	1 170 000		April	7 800	150	1 170 000
May	9 736	150	1 460 400		May			
June	9 736	150	1 460 400		June			
July	9 736	150	1 460 400		July			
August	9 736	150	1 460 400		August			
September	9 736	150	1 460 400		September			
Octomber	8 532	200	1 706 400		Octomber			
November	4 500	200	900 000		November			
December	4 500	200	900 000		December			
	90 766		13 479 800			24 554		2 961 800

The doctoral thesis envisages a scenario in which from 2024 to 2027 both the PhPP Bitola and the PhPP Oslomei-2 are expected to sell the produced electricity on the national market. It is planned for 2024 - 2027. the price in the winter months will be 200 euros/MWh, and in the rest 180 euros/MWh. [121-122]

With this way of forecasting the price of electricity to move from 2024 to 2027, the largest electricity producer JSC ESM in Macedonia will recover the investment in 3,3 years. However, the free electricity market is quite dynamic and unpredictable, if the forecasted monthly electricity prices are significantly lower, then the return on investment will be 5 to 7 years.

5.6. Conclusions to Chapter Five

Based on the information presented in this chapter, the following conclusions can be drawn:

1. Fifteen TS 10/0,8 kV/kV 2 500 kVA substations are planned for the PhPP Bitola, which will be connected to a new TS 110/10 kV/kV substation. This will be the third photovoltaic plant with such power and connected to the electricity grid.

2. Eight TS 35/0,8 kV/kV 2 500 kVA transformer stations are planned for the PhPP Oslomej, which will be connected to the existing TS Oslomej 110/35 kV/kV transformer station, whose voltage level 35 kV is owned by JSC ECM. In this way, a photovoltaic plant with a capacity of 20 MW will be connected to an electricity distribution network. In addition, connection costs are minimal.

3. The total investment for the two photovoltaic power plants PhPP Bitola 40 MW and PhPP Oslomej - 2.20 MW will amount to 43 543 298 euros including VAT, for a total of 60 MW installed. The MW price is 725 721 euros.

4. According to the estimated monthly prices for the sale of electricity on the free market, for the winter period of 200 EUR/MWh and for the other months of the year of 150 EUR/MWh, the return on investment is expected to be 3,3 years.

5. If it is taken into account that the life of the equipment is up to 25 years, this means that the remaining period of 21,7 years would be a net profit for JSC ESM.

CONCLUSION

Macedonia has not fully utilized the potential of solar energy on its territory. If PhPP Oslomej - 2, 20 MW and PhPP Bitola 40 MW are built and connected in the transmission system, the percentage share of electricity produced by the sun in relation to the total electricity produced in Macedonia will increase. Their construction would significantly reduce the import dependence of the Republic of North Macedonia. The cost of importing electricity will be significantly reduced.

The reason for the reduced production of electricity is the exhaustion of coal, its disappearance, as well as the low calorific value. The largest producer JSC ESM (previously the title was JSC ELEM) of electricity is to start the construction of new photovoltaic plants. Also JSC ESM must change its energy portfolio by increasing electricity production through the implementation of photovoltaic power plants. The construction of the new photovoltaic power plants PhPP Oslomei - 2, 20 MW and PhPP Bitola 40 MW is a project that can easily be implemented and would bring significant benefit to the Republic of Nort Macedonia. This would trigger the construction of other new, higher power PV plants connected to the power grid.

The construction of PhPP Bitola 40 MW and PhPP Oslomej - 2.20 MW, which are designed in this doctoral dissertation, are planned to be built with the funds of JSC ESM Macedonia. If we take into account the built photovoltaic power plants PhPP Bitola - Novaci MEJ and PhPP Oslomej, the total annual production of these PhPPs would amount to 239 000 MWh. In this case, electricity imports will decrease by 9,09% and domestic production will increase by 4,52%. As for the return on these two investments, it will be approximately three years and four months. In Macedonia, this is the beginning of the construction of large photovoltaic plants that will be connected to the electricity grid, and this will have a burdensome effect on the electricity transmission network and will create a need for the construction of a 110 kV connection, as well as the construction of TS 110/ 10 kV/kV , but this represents a typical problem of the energy transition in the field of the use of renewable sources and in particular solar energy.

With the construction of PhPP Bitola and PhPP Oslomei 2, other foreign investors will be encouraged to build photovoltaic power plants with large capacities. All this will be realized by leasing or concessioning land to foreign investors for a period of 40 years. Particularly attractive for investors are the regions with high solar radiation, such as the Pelagon region, the Polog region, the Stip and Valandovo valleys, where the solar radiation is over 1 700 kWh/m2. Also in the Republic of North Macedonia there is a Law on Strategic Investments, by which, if it is determined that the investment brings a huge benefit to the Republic of North Macedonia, the overall procedures that are carried out in the institutions are significantly shortened.

In the future, the possibility of storing electricity obtained from renewable sources should also be considered. In this way, the percentage share of electricity produced from renewable sources in the total electricity consumption will increase. Savings will increase, both financially and in terms of electricity consumption.

DISSERTATION CONTRIBUTIONS

Scientific and applied contributions

1. As a result of the detailed analytical study of the balance of electricity production and, in particular, of photovoltaic power plants in 4 countries on the Balkan Peninsula - the Republic of North Macedonia, Bulgaria, Serbia and Croatia, reasoned recommendations have been made for the construction of new photovoltaic power plants in Republic of North Macedonia.

2. A model of the electricity system of the Republic of North Macedonia was synthesized, enabling the analysis of changes in energy flows, energy losses and overvoltages in the power grid when connecting the newly designed photovoltaic power plants

Applied Contributions

1. The potential of solar radiation for the production of electrical energy from photovoltaic power plants on the territory of the Republic of North Macedonia was investigated.

2. Developed and detailed variant projects of 2 photovoltaic plants on the territory of the Republic of North Macedonia with a total capacity of 60 MWp, using 4 different variants of technologies and orientation of the photovoltaic modules.

3. A technical-economic analysis and evaluation of the profitability of the construction of the new 2 photovoltaic power plants on the territory of the Republic of North Macedonia was made, taking into account the dependence on the expected prices on the electricity market in the coming years.

LIST OF DISSERTATION PUBLICATIONS

[A1] Arsov B., **Arsova E.**, Sadinov S., Measurements of the non-ionizing radiation of 5G base station of mobile operator Makedonski Telekom AD Skopje and electricity supply with photovoltaic plant, EEPES.EU, International Conference on Electronics, Engineering, Physics and Earth Science, EEPES 2023 Conference, Scopus (ID144, page 19), Kavala, Greece, June 2023 (Indexing and Publishing AIP Conference Proceedings is indexing in: Scopus, CPCI (part of Web of Science), Inspec index, SJR 0.19) (in Print)
A certificate of acceptance of the publication is enclosed.
https://pubs.aip.org/aip/acp

[A2] **Arsova E**., Expansion of renewable energy sources in 2022 in the RN Macedonia, 7th International Scientific Conference – TechCo 2023, June 2023, Technical College Lovech – Bulgaria
https://www.tugab.bg/images/tk-lovech/programa_TechCo-2023_n.pdf

[A3] **Arsova E**., Electricity crisis in 2021 in the RN Macedonia and recommendations for the future, 7th International Scientific Conference – TechCo 2023, June 2023, Technical College Lovech – Bulgaria
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[A4] **Arsova E**., Tsankov P., Implementation of 40 MW photovoltaic power plant Bitola in RN Macedonia, International Scientific Conference UNITECH 2023, November 2023, Technical University in Gabrovo – Bulgaria
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[A5] **Arsova E**., Tsankov P., Design of 20 MW Photovoltaic power plant Oslomej in RN Macedonia, International Scientific Conference UNITECH 2023, November 2023, Technical University in Gabrovo – Bulgaria
https://unitech2023.tugab.bg/images/thematic-sessions/ELECTRICAL%20ENGINEERING/s1_p45_v3.pdf

Author's works related to the topic of the dissertation before enrolling the doctoral student

[1A] Natasha Veljanovska, *Elisabeta Arsova*, Marko Bislimoski, Dimitar Petrov, Elena Markova - Velinova - "Analysis of the impact of the purchase of electricity from preferential producers on the average price of electricity supply for tariff consumers in the Republic of Macedonia in 2011."- Cigre 2013; *ISBN* 978-80-89402-11-3

[2A] Natasha Veljanovska, *Elizabeta Arsova*, Marko Bislimoski, Svetlana Janevska, Kushtrim Ramadani - "The third package of legislation on electricity in the European Union" – Cigre 2013; *ISBN* 978-80-89402-11-3

[3A] Marko Bislimoski, Natasha Veljanovska, *Elizabeta Arsova*, Vidan Kulevski, Kushtrim Ramadani - "The impact of the new by-law price regulation/tariff regulation on final consumer prices"– Cigre 2013; ISBN 978-80-89402-11-3

[4A] *Elizabeta Arsova,* Marko Bislimoski, Natasha Veljanovska, Dimitar Petrov, Svetlana Janevska - "Registration of electricity market participants and formation of balance groups" – Cigre 2013; ISBN 978-80-89402-11-3

[5A] Marko Bislimoski, Natasha Veljanovska, *Elizabeta Arsova*, Vidan Kulevski, Elena Markova - Velinova - "Calculation of deviations of agreed and realized transactions“– Cigre 2013; ISBN 978-80-89402-11-3

[6A] Natasha Veljanovska, Marko Bislimoski, *Elizabeta Arsova*, Dimitar Petrov, Svetlana Janevska - "The impact of purchasing electricity produced by preferential producers" – Cigre 2015; ISBN 978-608-4578-07-9

[7A] Marko Bislimoski, Natasha Veljanovska, *Elizabeta Arsova*, Vidan Kulevski, Kushtrim Ramadavi - "Effects of the liberalization of the electricity market"– Cigre 2015; ISBN 978-608-4578-07-9

[8A] *Elizabeta Arsova,* Marko Bislimoski, Natasha Veljanovska, Elena Markova - Velinova, Kushtrim Ramadani - "Improving the way and conditions for connecting users to the electricity distribution network according to the Network Rules"– Cigre 2015; ISBN 978-608-4578-07-9

TITLE: „ANALYSIS OF THE OPPORTUNITIES FOR THE IMPLEMENTATION OF NEW PHOTOVOLTAIC POWER PLANTS IN THE ELECTRICAL ENERGY SYSTEM OF THE REPUBLIC OF NORTH MACEDONIA“

Author: Dipl. Eng. Elizabeta Trayko Arsova, MSc.

The object of research in the dissertation is the photovoltaic power plants and their commissioning, as new capacities in the electricity system of the Republic of North Macedonia, to replace the old non-ecological and polluting power plants with harmful emissions.

The main goal of the dissertation is to analyze the possibilities for implementing new photovoltaic power plants in the electricity system of the Republic of North Macedonia. To achieve the main goal, it is necessary to complete the following *tasks*:

1. To study good practices from the neighboring countries of the region and analyze the energy balance when implementing renewable sources of electricity in the Republic of North Macedonia.
2. To develop a methodology for studying the potential of solar radiation and simulating electricity production from photovoltaic systems on the territory of the Republic of North Macedonia.
3. To synthesize a scheme and model the operation of powerful photovoltaic plants on the territory of the Republic of North Macedonia.
4. To model the work and the energy balance of the Republic of North Macedonia after the accession of the newly built photovoltaic power plants, in order to analyze the changes in energy flows, energy losses and overvoltages in the power transmission network.
5. To carry out a technical and economic analysis of the construction of new photovoltaic power plants on the territory of the Republic of North Macedonia, depending on the expected prices that may reach in the coming years on the electricity market.

The research methods used in solving the tasks set in the dissertation are: theoretical analysis, computer design, modeling and simulation studies, using methods of mathematical statistics for data processing. Conceptual electrotechnical projects, simulation of the mode of operation of two new FPPs and their connection to the energy system of the Republic of North Macedonia, as well as a technical and economic analysis of the profitability of their construction, which improves the efficiency and infrastructure of the electricity supply to the population, have been implemented.

Scientific and applied contributions:

1. As a result of the detailed analytical study of the balance of electricity production and, in particular, of photovoltaic power plants in 4 countries on the Balkan Peninsula - the Republic of North Macedonia, Bulgaria, Serbia and Croatia, reasoned recommendations have been made for the construction of new photovoltaic power plants in Republic of North Macedonia.
2. A model of the electricity system of the Republic of North Macedonia has been synthesized, enabling the analysis of changes in energy flows, energy losses and overvoltages in the power transmission network when connecting the newly designed photovoltaic power plants.
3. The potential of solar radiation for the production of electrical energy from photovoltaic power plants on the territory of the Republic of North Macedonia was investigated.
4. Developed and detailed variant projects of 2 photovoltaic plants on the territory of the Republic of North Macedonia with a total capacity of 60 MWp, using 4 different variants of technologies and orientation of the photovoltaic modules.
5. A technical-economic analysis and evaluation of the profitability of the construction of the new 2 photovoltaic power plants on the territory of the Republic of North Macedonia was made, taking into account the dependence on the expected prices on the electricity market in the coming years.

Keywords: photovoltaic power plant, electric power distribution modeling and simulation, photovoltaic system design and simulation, PVGIS, PVsyst, PSS Siemens.