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REDUCING CLIMATE CHANGE BY INSTALLING A NEW PHOTOVOLTAIC POWER PLANT IN BULGARIA

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Summary: Three new roof-mounted 10 kWp grid-connected photovoltaic (PV) power plants have been constructed in the Technology Park at the Technical University of Gabrovo, Bulgaria, as part of a project "Competence Center – Intelligent Mechatronic, Eco, and Energy Saving Systems and Technologies". Three different PV modules types have been used: monocrystalline silicon (mono-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). New three power plants, together with the existing amorphous silicon and poly-crystalline silicon photovoltaic power plants at the TU-Gabrovo enhanced simultaneous testing of five different photovoltaic materials. A small 500 Wp mono-Si photovoltaic thermal hybrid solar collectors (PVT) PV system has also been constructed. The power plants feature a monitoring system for the meteorological and electrical operating parameters, which measures, displays, and stores data on solar radiation, temperature, wind speed, currents, voltages, and electrical power of each power plant. PV plants components' technical characteristics are given in the paper. The schemes describing the basic wiring diagram, disposition of the three PV subsystems on the roof of the building at the technology center have also been presented. The initial comparative software data for monitoring of meteorological and electrical operating characteristics of the three different types of PV subsystems are shown as well. According to the specific ecological equivalent of energy resources and energy for the region of Bulgaria, the data are presented on the saved CO2 emissions from the avoided production and transmission of electricity owing to the operation of photovoltaic power plants.

Keywords: monocrystalline silicon, cadmium telluride, copper indium gallium selenide, grid-connected photovoltaic power plant, monitoring system, meteorological and electrical operating characteristics, smart solar logger, carbon emissions, climate change.

1. INTRODUCTION

Exploring the possibilities and technical solutions influencing climate change by using renewable energy sources, in particular - photovoltaic (PV) systems, is the most common contemporary scientific research topic [1–5]. The potential for photovoltaic power plants influencing climate change depends on the production share by types of power plants in the specific region.

Bulgaria has taken an active role in the international efforts to help prevent climate change by supporting the concerted actions of the European Union and the wide-ranging package of measures in the energy sector. The widespread use of renewable energy sources (RES) and the implementation of energy efficiency measures are among the priorities of the national energy policy and are complying with the objectives of the new energy policy for Europe. As a result of the introduction of the Feed-in Tariff (FiT) in 2008, photovoltaic power plants' total power exceeding 1 GW were constructed in Bulgaria. In 2014, the FiT was dropped out for all ground-based and roof installed PV power plants over 30 kWp. At present, FiT exists only for small roof and facade photovoltaic systems [6]. This financial motivation, together with the reduction in prices of equipment for PV power plants, has led in recent years to the construction of a large number of small PV power plants capacity of less than 30 kWp on the roofs of buildings and adjacent areas. This has caused current interest and the increased importance of this type of study of PV power plants in Bulgaria, the example of which is given in this publication.

The three new roof-mounted 10 kWp grid-connected photovoltaic power plants have been constructed in the Technology Park at the Technical University of Gabrovo, Bulgaria, as part of a project

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„Competence Center – Intelligent Mechatronic, Eco, and Energy Saving Systems and Technologies”. Three different PV modules types have been used: mono-crystalline silicon (mono-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). New three power plants, together with the existing amorphous silicon and poly-crystalline silicon photovoltaic power plants at the TU-Gabrovo, enhanced simultaneous testing of five different photovoltaic materials. A small 500 Wp mono-Si photovoltaic thermal hybrid solar collectors (PVT) PV system has also been constructed. The power plants feature a monitoring system for the meteorological and electrical operating parameters, which measures, displays, and stores data on solar radiation, temperature, wind speed, currents, voltages, and electrical power of each power plant.

2. DESIGN AND TECHNICAL DATA FOR THE PHOTOVOLTAIC POWER PLANTS CONSTRUCTED

The modules of the three roof photovoltaic power plants are mounted on the metal constructions – Figure 1-a). The tilt angle of the photovoltaic modules related to the horizon is 33°. As a result of design considerations, the orientation of the photovoltaic modules is deviated by 18.4° degrees to the east – Figure 1-b).

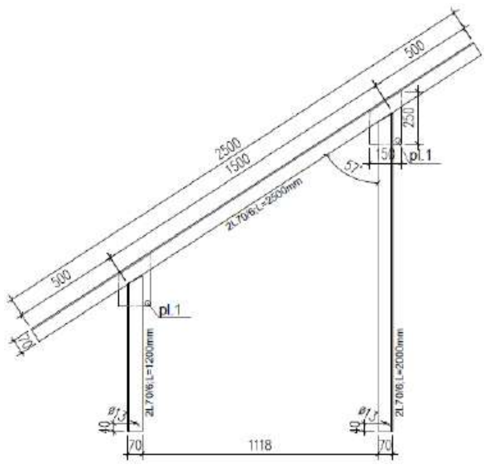


Figure 1-a). Roof metal construction for the photovoltaic power plants

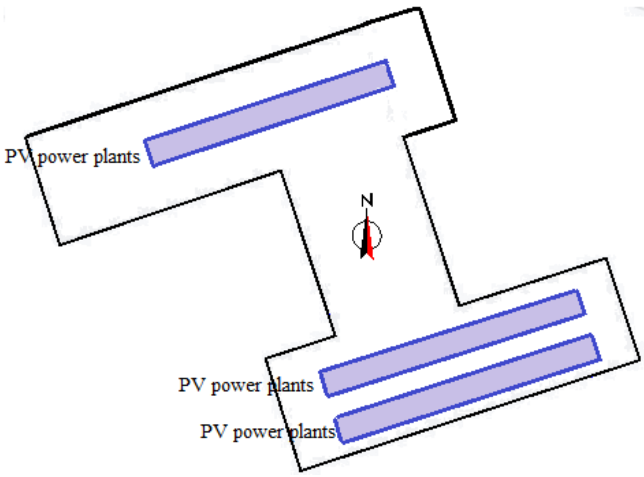


Figure 1-b). Orientation of the photovoltaic systems

Three different PV modules types of the constructed power plants have been used – mono-Si, CdTe, and CIGS. Technical data at standard test conditions (STC) of the three different PV modules types are shown in Table 1 [7,8].

The disposition of the three PV power plants on the roof of the Competence Center building at the Technology Center of the Technical University of Gabrovo is shown in Figure 2.

The roof mono-Si power plant consists of 44 PV modules with maximum power of 10 kWp (Figure 2 and 3). The I-V curves of the mono-Si PV module at different solar irradiation and different cell temperatures are shown in Figure 4.

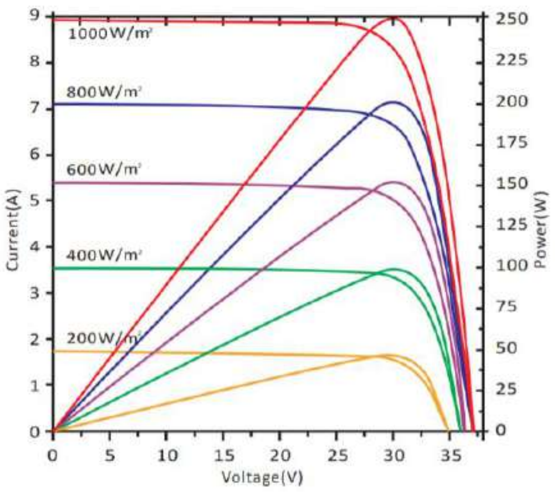
Table 1. Technical data at STC of the three different PV modules types

Parameters at STC*	mono-Si by Risen, model SYP250M	CdTe by Calyxo, model CX4 100/3	CIGS by Hulket, model 1100E1
Nominal power, [Wp]	250.00	100.00	110.00
Voltage at maximum power [V]	30.40	72.60	56.90
Current at maximum power [A]	8.25	1.38	1.93
Open circuit voltage [V]	37.50	72.60	73.40
Short circuit current [A]	8.59	1.53	2.10
Maximum system voltage [Vdc]	1000	1000	1000
*Notes – STC at: Solar irradiance: 1000 W/m^2, Air mass: AM = 1.5, PV cell temperature: T_c = 25 °C			

Figure 2. Disposition of the three PV power plants on the roof of the Competence Center building at the Technology Park of the Technical University of Gabrovo, Bulgaria

The roof CdTe power plant consists of 96 PV modules with maximum power of 9.6 kWp (Figure 2 and 5). Figure 6 shows relative efficiency at different cell temperatures of the CdTe PV module 100 Wp, model CX4 100/3, Figure 7 shows comparative efficiency at different temperatures of the PV cell between CdTe and crystalline (c-Si) silicon material. At PV cells temperatures above 75 °C in the operating zone of Figure 6, the efficiency of the CdTe PV modules is higher than c-Si PV modules.

Figure 3. Mono-Si PV modules power plant



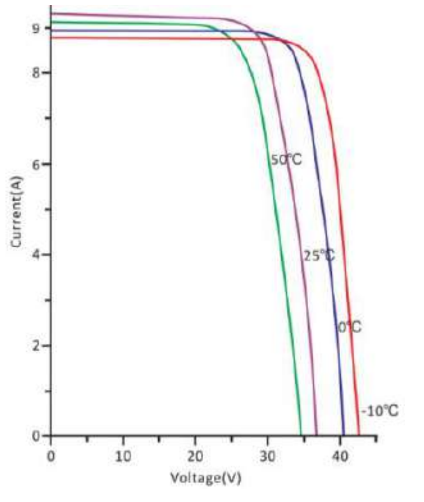


Figure 4-a) *Figure 4-b)*

Figure 4. I-V curves of the mono-Si PV module at different irradiation – a) and PV cell temperatures – b)

Figure 5. CdTe PV modules power plant

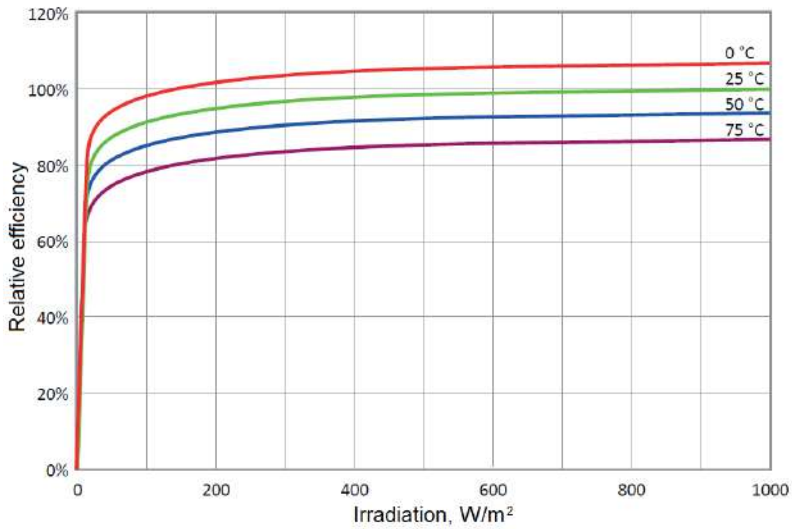


Figure 6. Performance at different cell temperatures of the CdTe PV module 100 Wp

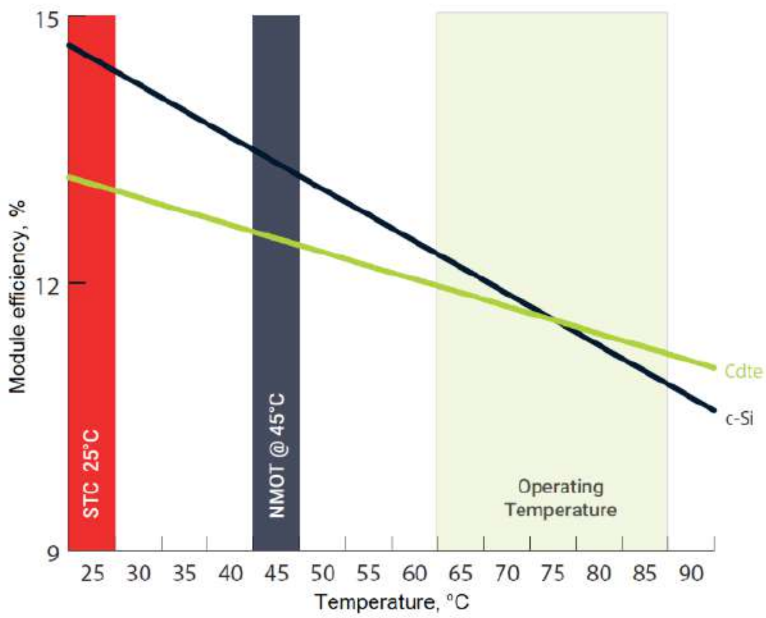


Figure 7. Comparative efficiency at different PV cell temperatures between CdTe and crystalline silicon material

The CIGS power plant roof consists of 90 PV modules with maximum power of 9.9 kWp (Figure 2 and 8). I-V curves of the CIGS PV module – model 1100E1, at different solar irradiation and PV cell temperature are shown in Figure 9.

A small 500 Wp mono-Si photovoltaic-thermal hybrid solar collectors (PVT) PV system is also constructed – Figure 2, and connected to a separate grid-connected inverter Fronius Galvo 2.5.

The three rooftop PV subsystems are connected to the three sine-wave three-phase grid-tied PV string inverters, model SUN2000-10KTL-M0 (Huawei), which converts DC power generated by the three PV subsystems of different type of PV technologies into AC power, feeding it into the power grid. The grid-connected PV string inverters synchronize electrical parameters with the power grid. The disposition of the three grid-tied PV string inverters and their appearance is shown in Figure 10.

Figure 8. CIGS PV modules power plant

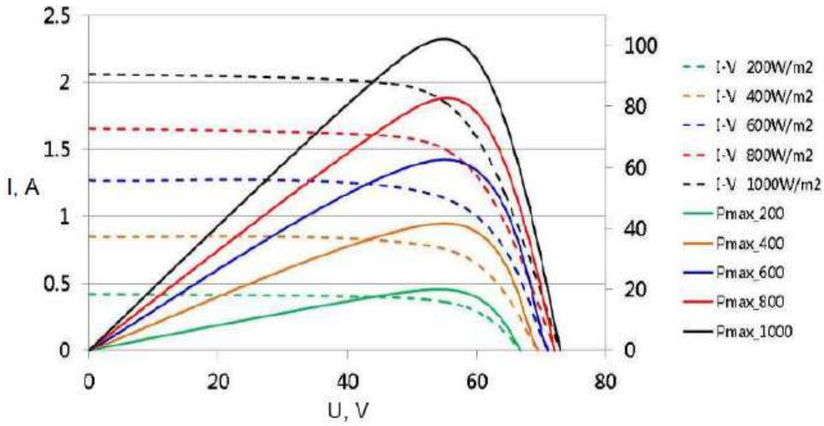


Figure 9-a)

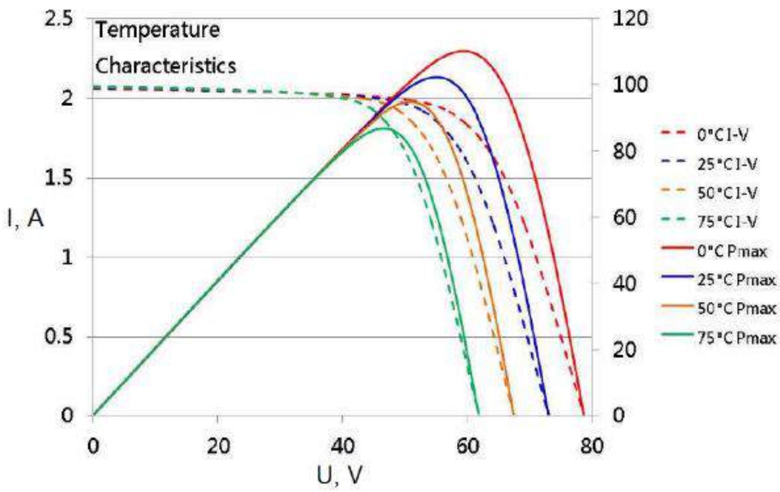


Figure 9-b)

Figure 9. I-V curves of the CIGS PV module at different irradiation – a) and PV cell temperatures – b)

Figure 10. Disposition of the three-phase grid-tied PV string inverters and appearance of the model SUN2000-10KTL-M0

Table 2. Technical data of the sine-wave three-phase grid-tied PV string inverters, model SUN2000-10KTL-M0

Input		Output	
Maximum PV power	14,880 Wp	Grid connection	3 phase
Maximum voltage	1,100 Vdc	Rated output power	10 kW
Operating voltage range	(140 ÷ 980) V	Maximum apparent power	11 kVA
Start-up voltage	200 V	Rated output voltage	230/400 Vac
Full power MPPT voltage range	(470 ÷ 850) V	Rated AC grid frequency	50 Hz
Rated input voltage	600 V	Maximum output current	16.9 A
Maximum input current / MPPT	11 A	Adjustable power factor (PF)	0.8 ind ÷ 0.8 cap
Maximum short-circuit current	15 A	Maximum total harmonic distortion (THD)	≤ 3 %
Number of MPP trackers	2	Maximum efficiency	98.6 %
Maximum number of inputs	2		

The roof PV power plants are equipped with a monitoring system for the meteorological and electrical operating parameters, which measures, displays, and stores data on solar radiation, temperature, wind speed, currents, voltages, and electrical power of each power plant. The monitoring system with a smart logger, model Solar-Log 300 [9] – Figure 11, includes remote alarm function and graphic evaluation on PC. The main technical data of the three sine-wave, three-phase grid-tied PV string inverters, model SUN2000-10KTL-M0, are shown in Table 2 [10]. Efficiency curves of the inverters SUN2000-10KTL-M0 at different values of the input voltage are shown in Figure 12.

The electrical connection diagram of the individual strings for the CdTe and CIGS PV module is shown in Figure 13. Grounding is done for the installation.

Communications with the inverters SUN2000-10KTL-M0 and smart logger Smart-Log 300 can be performed with access over a public network (Figure 14), and by access over a local ethernet and Wi-Fi (Figure 15).

Figure 11. The monitoring system of the PV power plants with model Solar-Log 300

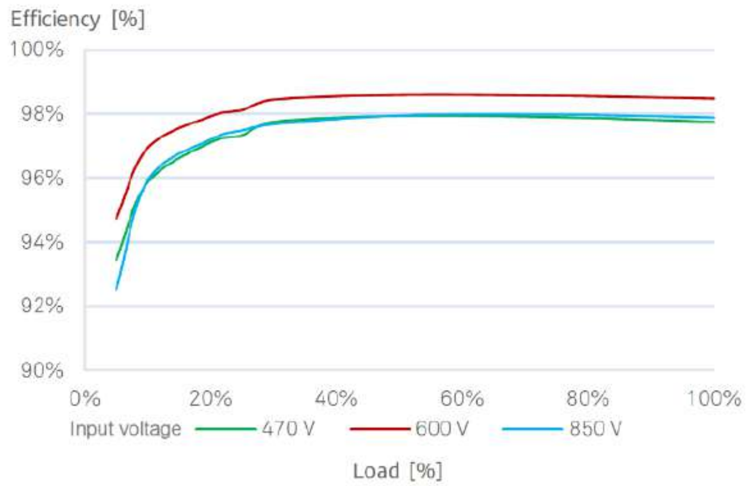


Figure 12. Efficiency curves of the inverters SUN2000-10KTL-M0 at different input voltage

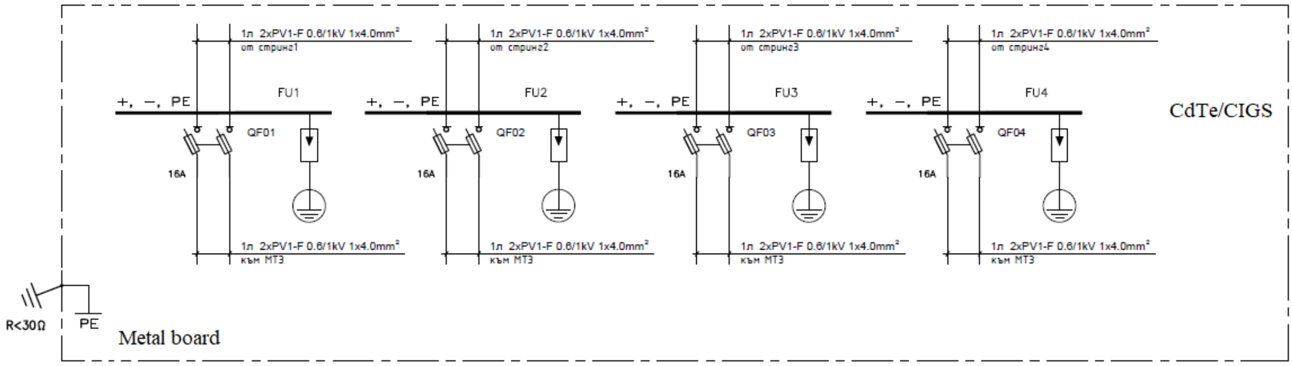


Figure 13. Schemes describing basic wiring diagram of the individual strings for CdTe and CIGS PV module

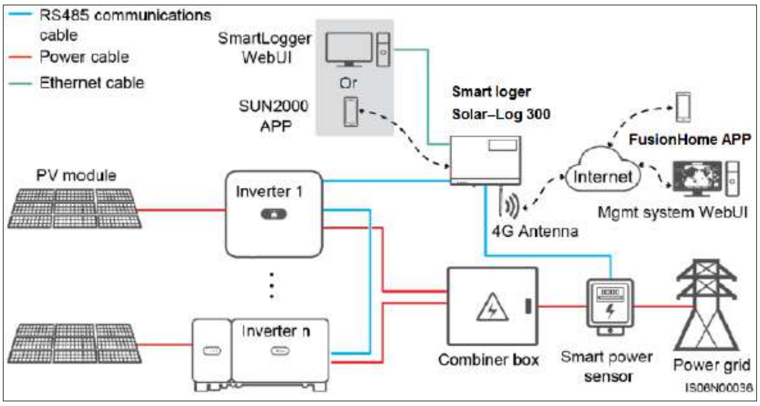


Figure 14. Communications with the inverters and smart logger by access over a public network

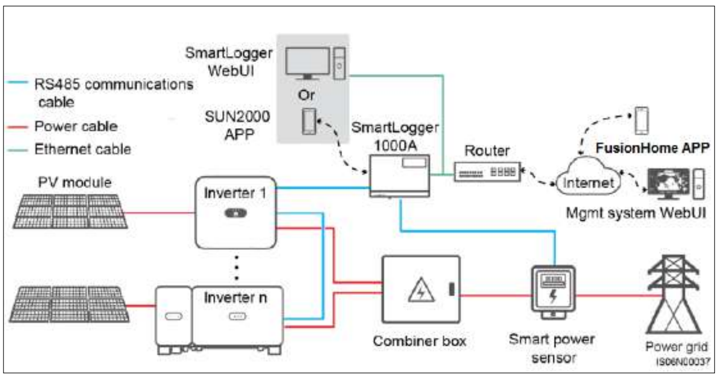


Figure 15. Communications with inverters by access over a local ethernet and Wi-Fi

2. INITIAL MONITORING SOFTWARE DATA FOR METEOROLOGICAL AND ELECTRICAL PARAMETERS

The monitoring system of the roof PV power plants is performed in two ways: through direct communication with the three-phase sine-wave inverters via RS485, WLAN, Wi-Fi/4G, or via mobile FusionSolar App and detail monitoring from smart logger Solar-Log 300. Figure 16 shows direct communications with inverters SUN2000-10KTL-M0 over Wi-Fi with FusionHome App. The mobile app displays grid-connected, daily, monthly, and annual energy yields. The roof PV power plants were put into operation in May 2020.

The detailed data for the meteorological and electrical operating parameters of the roof PV power plants are received from smart logger Solar-Log 300. The monitoring system by the smart logger measures, displays in real-time and stores data on solar radiation, temperature, wind speed, currents, voltages, electrical power, energy yield, and registered events of each power plant. Figures 17 and 18 show monitoring in real-time of the yield data and energy flow from the PV power plants to the power grid.

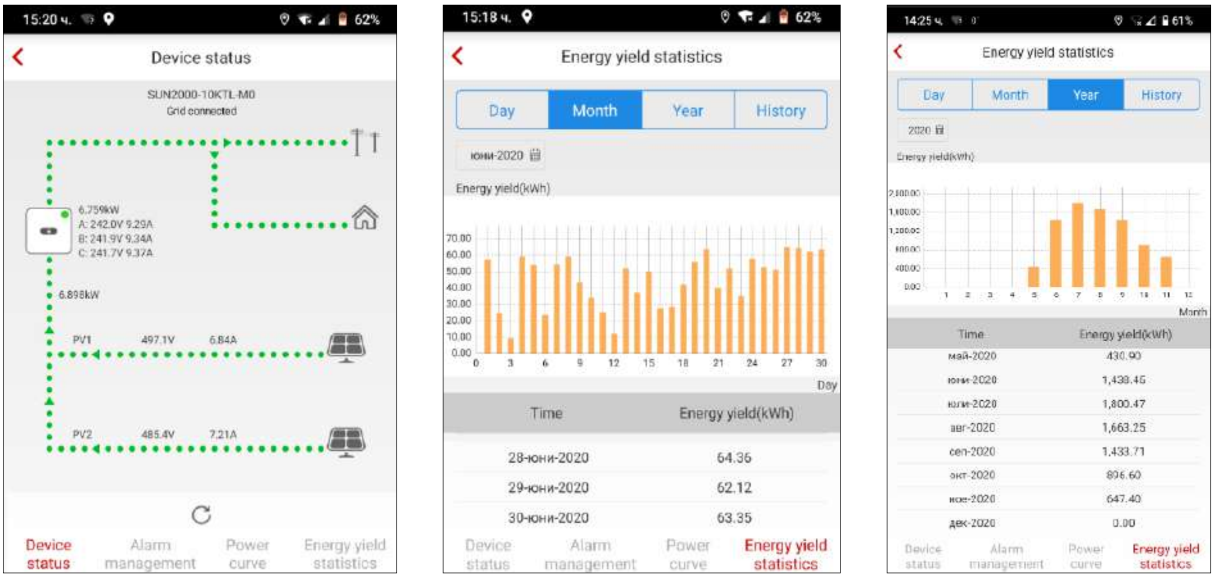


Figure 16. Communications with inverters SUN2000-10KTL-M0 over Wi-Fi with FusionHome App

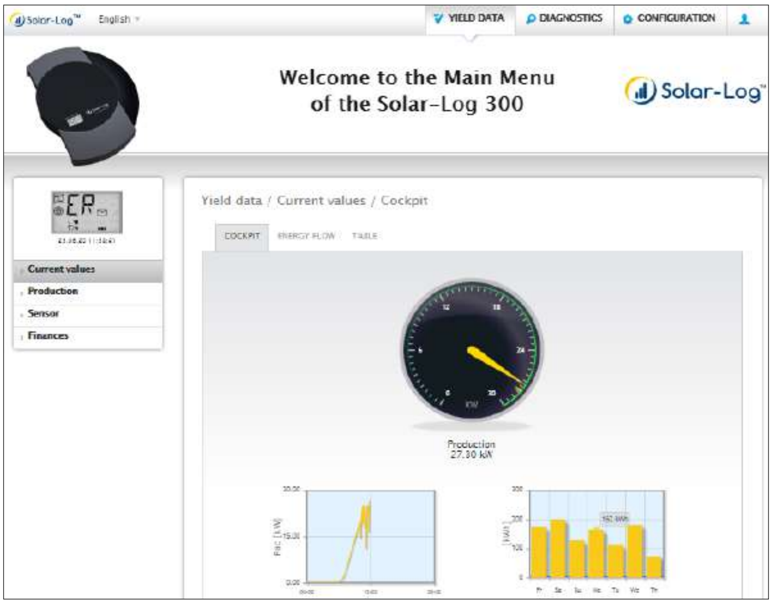


Figure 17. Monitoring of the yield data

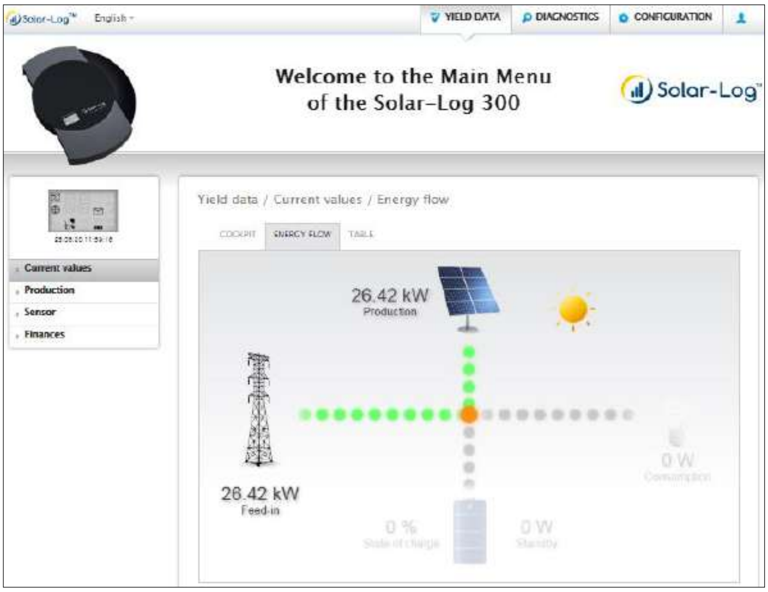


Figure 18. Energy flow monitoring

The monitoring system displays details individually for each inverter as status (on-grid or off-grid), the daily change of the input DC voltage, currents, powers, and AC output AC and temperature – Figure 19 and 20. The values can be displayed for a selected period. The monitoring software system visualizes daily, monthly, and annual electricity production of the PV power plants. All the values of the electrical parameters, temperature, solar irradiation, status of the inverters, errors, and events are stored and can be exported to CSV file – Figure 21. When the actual yield differs from the target yield, the monitoring system sends a notification (email message, etc.).

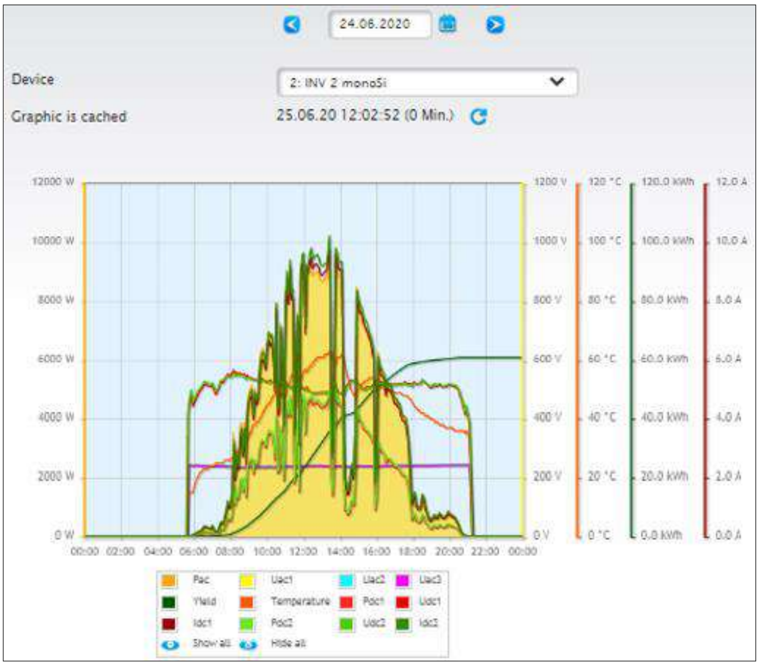
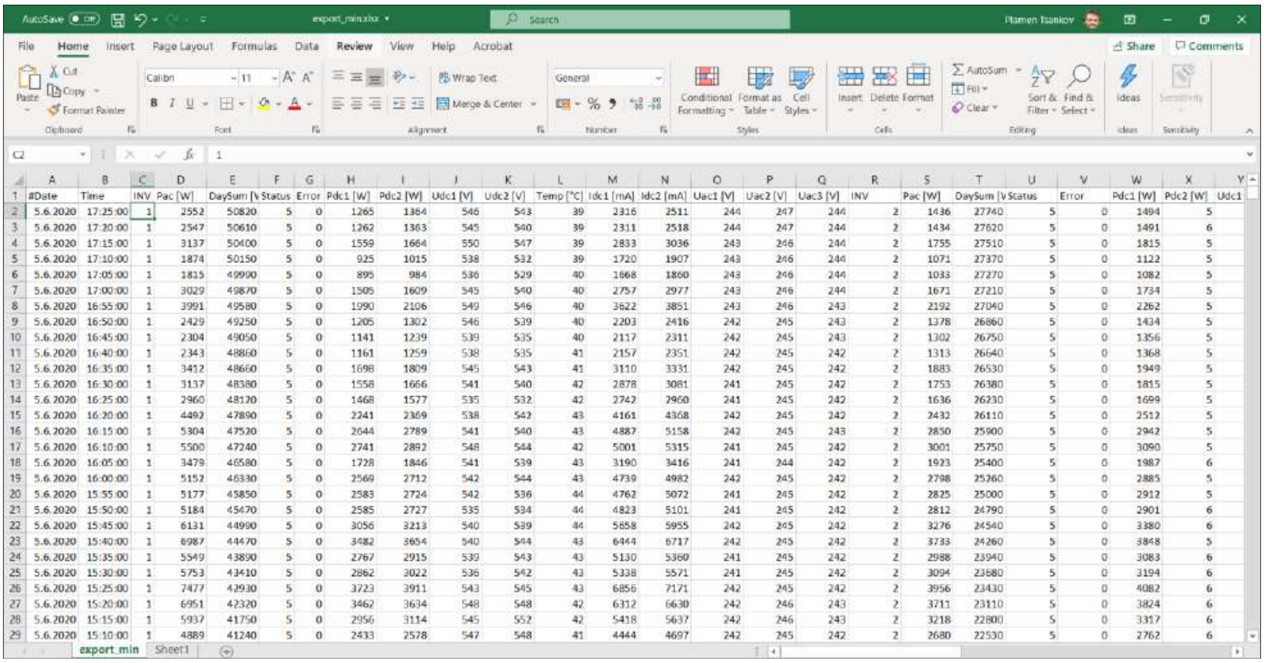


Figure 19. The inverter details of the mono-Si PV modules power plant

Figure 20. The inverter details of the CIGS PV modules power plant



#Date	Time	INV	Pac [W]	DaySum [V	Status	Error	Pdc1 [W]	Pdc2 [W]	Udc1 [V]	Udc2 [V]	Temp [°C]	Idc1 [mA]	Idc2 [mA]	Uac1 [V]	Uac2 [V]	Uac3 [V]	INV	Pac [W]	DaySum [V	Status	Error	Pdc1 [W]	Pdc2 [W]
5.6.2020	17:25:00	1	2552	50820	5	0	1265	1364	546	543	39	2316	2511	244	247	244	2	1436	27740	5	0	1494	5
5.6.2020	17:20:00	1	2547	50610	5	0	1262	1363	545	540	39	2311	2518	244	247	244	2	1434	27620	5	0	1491	6
5.6.2020	17:15:00	1	3137	50400	5	0	1559	1664	550	547	39	2833	3036	243	246	244	2	1755	27510	5	0	1815	5
5.6.2020	17:10:00	1	1874	50150	5	0	925	1015	538	532	39	1720	1907	243	246	244	2	1071	27370	5	0	1122	5
5.6.2020	17:05:00	1	1815	49990	5	0	895	984	536	529	40	1868	1860	243	246	244	2	1033	27270	5	0	1082	5
5.6.2020	17:00:00	1	3029	49870	5	0	1505	1609	545	540	40	2757	2977	243	246	244	2	1671	27210	5	0	1734	5
5.6.2020	16:55:00	1	3991	49580	5	0	1990	2106	549	546	40	3622	3851	243	246	243	2	2192	27040	5	0	2262	5
5.6.2020	16:50:00	1	2429	49250	5	0	1205	1302	546	539	40	2203	2416	242	245	243	2	1378	26860	5	0	1434	5
5.6.2020	16:45:00	1	2304	49050	5	0	1141	1239	539	535	40	2117	2311	242	245	243	2	1302	26750	5	0	1356	5
5.6.2020	16:40:00	1	2343	48860	5	0	1161	1259	538	535	41	2157	2351	242	245	242	2	1313	26640	5	0	1368	5
5.6.2020	16:35:00	1	3412	48660	5	0	1698	1809	545	543	41	3110	3331	242	245	242	2	1883	26530	5	0	1949	5
5.6.2020	16:30:00	1	3137	48380	5	0	1558	1666	541	540	42	2878	3081	241	245	242	2	1753	26380	5	0	1815	5
5.6.2020	16:25:00	1	2960	48120	5	0	1468	1577	535	532	42	2742	2960	241	245	242	2	1636	26230	5	0	1699	5
5.6.2020	16:20:00	1	4492	47890	5	0	2241	2369	538	542	43	4161	4368	242	245	242	2	2432	26110	5	0	2512	5
5.6.2020	16:15:00	1	5304	47520	5	0	2644	2789	541	540	43	4887	5158	242	245	243	2	2850	25900	5	0	2942	5
5.6.2020	16:10:00	1	5500	47240	5	0	2741	2892	548	544	42	5001	5315	241	245	242	2	3001	25750	5	0	3090	5
5.6.2020	16:05:00	1	3479	46580	5	0	1728	1846	541	539	43	3190	3416	241	244	242	2	1923	25400	5	0	1987	6
5.6.2020	16:00:00	1	5152	46330	5	0	2569	2712	542	544	43	4739	4982	242	245	242	2	2798	25260	5	0	2885	5
5.6.2020	15:55:00	1	5177	45850	5	0	2583	2724	542	536	44	4762	5072	241	245	242	2	2825	25000	5	0	2912	5
5.6.2020	15:50:00	1	5184	45470	5	0	2585	2727	535	534	44	4823	5101	241	245	242	2	2812	24790	5	0	2901	6
5.6.2020	15:45:00	1	6131	44990	5	0	3056	3213	540	539	44	5658	5955	242	245	242	2	3276	24540	5	0	3380	6
5.6.2020	15:40:00	1	6987	44470	5	0	3482	3654	540	544	43	6444	6717	242	245	242	2	3733	24260	5	0	3848	5
5.6.2020	15:35:00	1	5549	43890	5	0	2767	2915	539	543	43	5130	5360	241	245	242	2	2988	23940	5	0	3083	6
5.6.2020	15:30:00	1	5753	43410	5	0	2862	3022	536	542	43	5338	5571	241	245	242	2	3094	23680	5	0	3194	6
5.6.2020	15:25:00	1	7477	42930	5	0	3723	3911	543	545	43	6856	7171	242	245	242	2	3956	23430	5	0	4082	6
5.6.2020	15:20:00	1	6951	42320	5	0	3462	3634	548	548	42	6312	6630	242	246	243	2	3711	23110	5	0	3824	6
5.6.2020	15:15:00	1	5937	41750	5	0	2956	3114	545	552	42	5418	5637	242	246	243	2	3218	22800	5	0	3317	6
5.6.2020	15:10:00	1	4889	41240	5	0	2433	2578	547	548	41	4444	4697	242	245	242	2	2680	22530	5	0	2762	6

Figure 21. CSV export data of the monitoring system

4. ASSESSMENT OF THE ECOLOGICAL EQUIVALENT OF THE SAVED ENERGY IN BULGARIA

In Bulgaria, a mandatory state „Ordinance № E-RD-04-3 of 4 May 2016 on the eligible measures for the implementation of energy savings in final consumption, ways of demonstrating the energy savings achieved, the requirements for their assessment methodologies and methods of confirmation" [11] is in force. This state ordinance includes Appendix 3 with Reference values of the conversion factor considering the losses for extraction/production and transmission of energy, including fuels, and Appendix 4 with Reference values of the ecological energy equivalent coefficient for different fuels (Table 3). A Specialized Commission on Electricity at the National Agency for Sustainable Energy Development, together with the author of this publication, has developed, according to the Ordinance, a Methodology for estimating energy savings when installing photovoltaic systems [12].

Table 3. Reference values of the conversion factor considering the losses for extraction/production and transmission of energy, including fuels, and Reference values of the ecological energy equivalent coefficient

Type of energy resource/ energy	The conversion factor from FES to PES, considering energy losses	Ecological equivalent coefficient
	e_p	f_i
	[-]	[gCO_2/kWh]
Industrial gas oil, diesel	1.10	267
Fuel oil	1.10	279
Natural gas	1.10	202
Propane-butane	1.10	227
Black coal	1.20	341
Lignite/brown coal	1.20	364
Anthracite coal	1.20	354
Coal briquettes	1.25	351
Firewood, pellets	1.05	43
The heat from district heating	1.30	290
Electrical energy	3.00	819

The initial data analysis of the new photovoltaic power plant monitoring systems in the Technology Park of the Gabrovo Technical University allows calculation of the parameters necessary to assess their impact on reducing carbon emissions and climate change. Figure 22 shows the web-view of the monitoring software for the 30 kWp (mono-Si, CdTe and CIGS) grid-connected power plants on the roof of the Gabrovo Tech Park, showing CO_2 emissions avoided from the launch of the power plant in May 2020 until July 2021, totaling 32.14 tons.

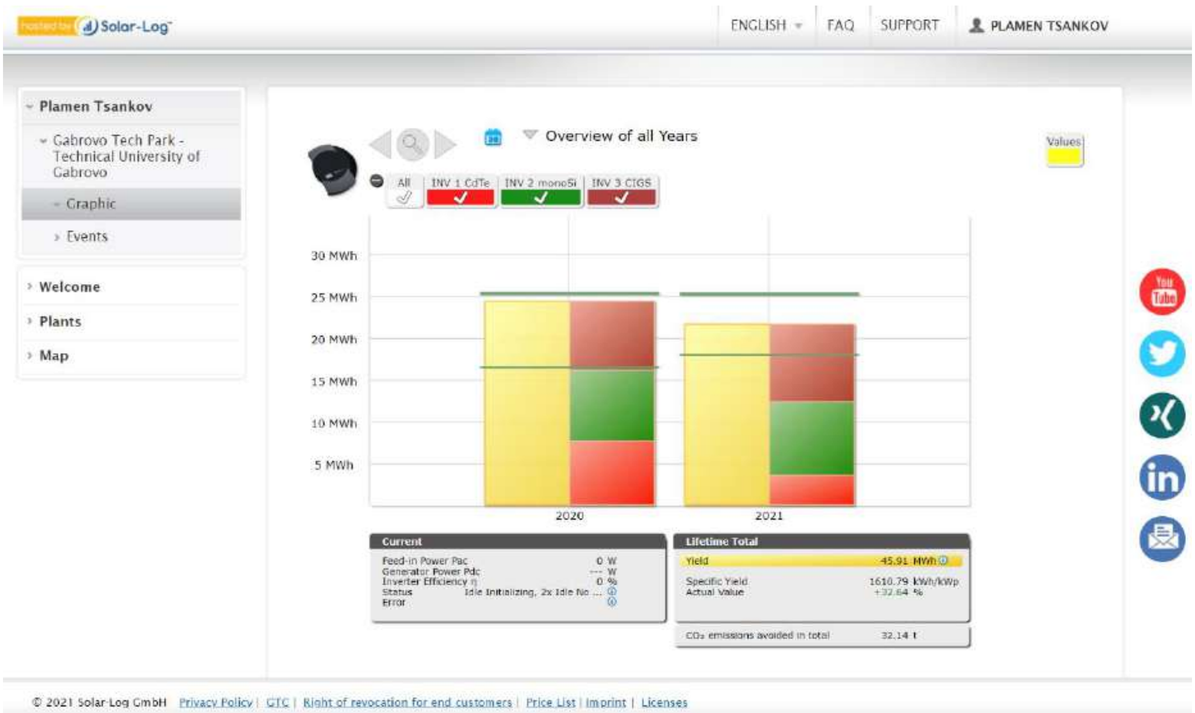


Figure 22. Monitoring software for the 30 kWp grid-connected power plant on the roof of the Gabrovo Tech Park showing CO_2 emissions avoided from the launch of the power plant in May 2020 until July 2021

The Android (Figure 23 - left) and Web-based (Figure 23 – right) monitoring software for the small hybrid PVT system (Figure 2) are also configured to directly calculate the environmental benefits of its operation. Figure 23 shows an exemplary screenshot indicating the saved kilograms of CO_2 emissions from the beginning of the system operation, as well as the corresponding number of saved trees or gained kilometers of movement of an airplane or a car with an internal combustion engine. The saved CO_2 emissions from the launch of the power plant in May 2020 until July 2021 are about 950 kilograms.

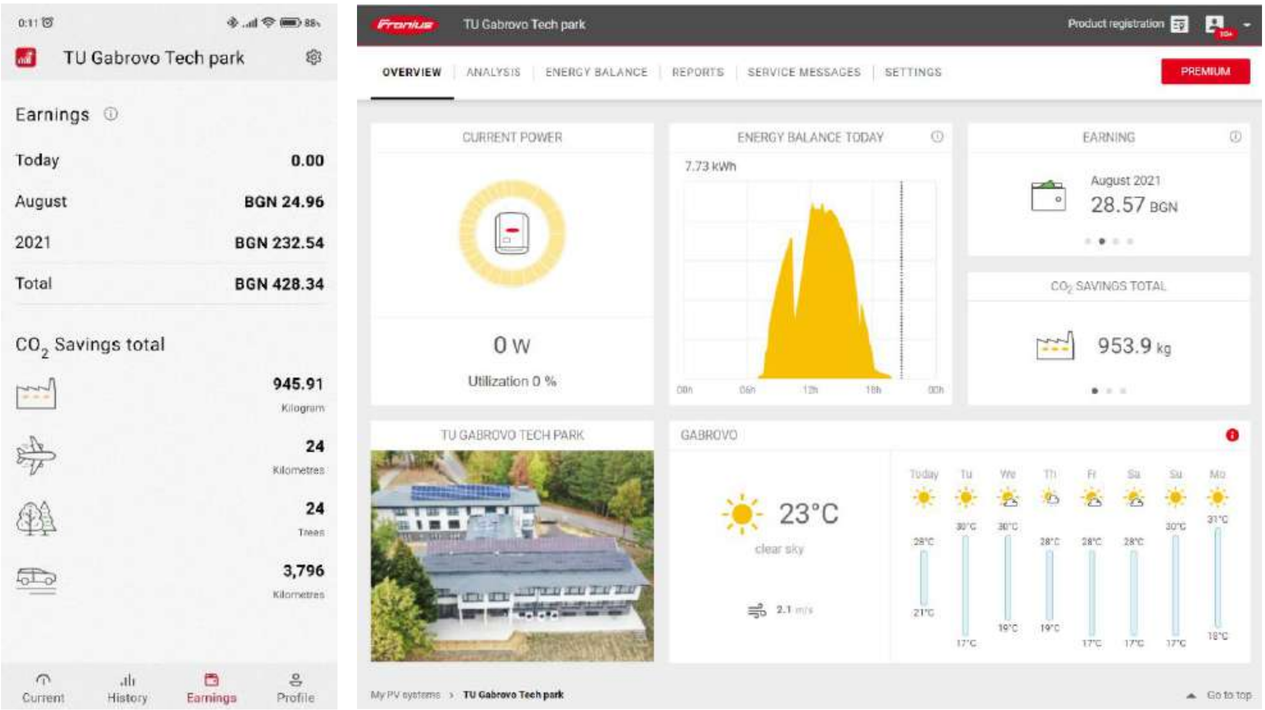


Figure 23. Monitoring software for the PVT system showing environmental benefits of its operation

4. CONCLUSIONS

With the construction of the new three mono-Si, CdTe, and CIGS power plants presented, together with the existing a-Si and p-Si modules photovoltaic power plants, five different photovoltaic materials can be tested simultaneously in the new laboratory at the Technology Park of the Technical University of Gabrovo. The initial measured and stored comparative data from monitoring software for meteorological and electrical operating parameters of the three different PV module materials of solar radiation, temperature, wind speed, currents, voltages, and electrical power of each power plant confirm the operability and functionality for the future research of the new photovoltaic power plants constructed. Their modern monitoring systems for the meteorological and electrical operating parameters allow for a detailed analysis of the produced electricity and an assessment of the impact on climate change of a similar type of widespread roof-mounted PV power plants in Bulgaria.

The carbon savings achieved by the small rooftop photovoltaic power plants in the current study are relatively small for major impacts on climate change but are useful in assessing the savings potential of different photovoltaic module technologies. The considered technical solutions for roof PV power plants power up to 30 kWp and their results are significant for the current stage of development of photovoltaic electricity in Bulgaria since FiT still applies only for such power plants. A study on the register of newly built photovoltaic power plants in Bulgaria [13] shows that, in 2020, 759 new ones were built, out of which 727, or 96%, have a capacity of up to 30 kWp.

The technical solutions developed in this study and the results obtained can be useful for the correct choice of the photovoltaic modules technology and other elements of the photovoltaic power plants, as well as for assessing their impact on climate change in Bulgaria and other regions with similar weather conditions, and the profiles of energy sources in their electricity systems.

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СМАЊЕЊЕ НИВОА КЛИМАТСКИХ ПРОМЈЕНА ИНСТАЛИРАЊЕМ НОВЕ ФОТОНАПОНСКЕ ЕЛЕКТРАНЕ У БУГАРСКОЈ

Сажетак: Три нове кровне фотонапонске (ПВ) електране од 10 kWp повезане на дистрибутивну мрежу изграђене су у Технолошком парку на Техничком универзитету у Габрову, Бугарска, а у склопу пројекта „Центар компетенција – интелигентни мехатронички системи, еколошки системи и системи за уштеду енергије и технологије". Коришћена су три различита типа фотонапонских модула: монокристални силицијум (моно-Si), кадмијум-телурид (CdTe) и бакар-индијум-галијум-селенид (ЦИГС). Нове три електране, уз постојеће фотонапонске електране на аморфни силицијум и поликристални силицијум у ТУ-Габрово, побољшале су синхронизовано тестирање пет различитих фотонапонских материјала. Изграђен је и мањи, моно-SI фотонапонски термо-хибридни систем соларних колектора (ПВТ) вршне снаге од 500 Wp. Електране имају систем за праћење метеоролошких и електричних параметара рада који мјери, приказује и похрањује податке о сунчевом зрачењу, температури, брзини вјетра, струјама, напонима и електричној снази сваке електране. У раду су наведене техничке карактеристике компоненти фотонапонских постројења. Приказане су и шеме које описују основну шему инсталација и распоред три фотонапонска подсистема на крову зграде у технолошком центру. Приказани су и почетни упоредни софтверски подаци за праћење метеоролошких и електричних радних карактеристика три различита типа фотонапонских подсистема. Такође, приказани су и подаци о емисијама CO_2 из производње и преноса електричне енергије избјегнутих захваљујући раду фотонапонских електрана, при чему су подаци добијени на основу специфичног еколошког еквивалента енергетских ресурса и енергије за подручје Бугарске.

Кључне ријечи: монокристални силицијум, кадмијум-телурид, бакар-индијум-галијум-селенид, фотонапонска електрана повезана на дистрибутивну мрежу, систем

за надзор, метеоролошке и електричне радне карактеристике, паметни соларни уређај за биљежење података, емисије угљеника, климатске промјене.

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