POLITECHNIKA GDAŃSKA
WYDZIAŁ CHEMICZNY

RENEWABLE ENERGY SOURCES LABORATORY

Department of Chemical Apparatus and Theory of Machines

Faculty of Chemistry, Gdańsk University of Technology

LABORATORY INSTRUCTION NO. 11-FR

USING THE APPLICATION INTEGRATED WITH A 2 kWp PHOTOVOLTAIC INSTALLATION

1. Purpose & range of the exercise

The exercise aims to familiarize students with the following topics:

- Working with the application connected to a photovoltaic plant.
- Calculating the electric parameters of a photovoltaic plant under actual operating conditions.
- Analysis of energy generated by a photovoltaic plant in relation to data obtained from PV-GIS.

2. Scope of exercise

The principle of solar cell operation is based on photovoltaic effect, namely direct conversion of solar radiation energy to electric energy. Semiconductor material absorbs photon energy, which results in releasing electrons from interatomic chemical bonds. However, not all of the semiconductors can be used in photovoltaic cell production. It is primarily dependent on energy gap, E_g. Lower values of E_g permit wider solar spectrum to be absorbed, but at the same time it is linked to lower photovoltaic voltage generation [1][2]. Appropriate adjustment of solar battery's spectral sensitivity to spectral radiation characteristics is an extremely important aspect. Nowadays, around 90% of Polish market consists of silicon based mono- and polycrystalline first generation modules, while the rest belongs to second generation amorphous silicon ($a-Si$), copper indium selenide (CIS) and copper indium gallium selenide (CIGS) [3]. The scheme of the photovoltaic cell structure is presented in Figure 1.

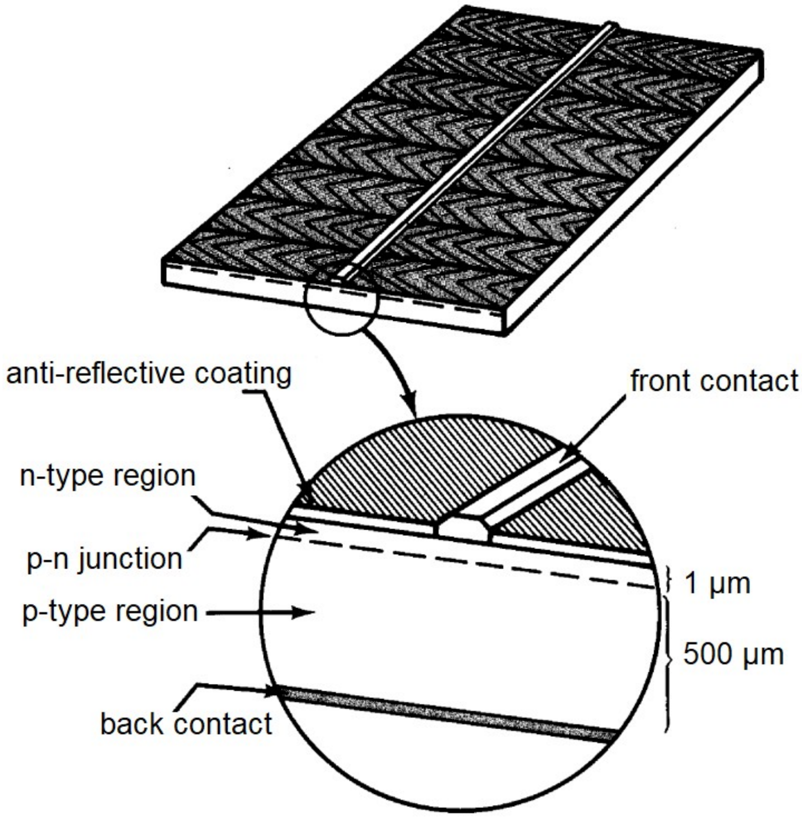


Fig. 1. Silicon based photovoltaic cell layout [4]

The primary element of solar cell is p-n junction, as shown in Figure 2. In the silicon based solar battery electron and hole conductivity are obtained by doping the material with phosphorus and boron respectively. At room temperature it may be assumed that all acceptor dopants n_A in type p semiconductor and donor dopants n_D in type n semiconductor are ionised. Then, there are grounds for applying such an approximation that equates concentration of majority carriers to their dopants. Once p-n junction is formed, there is a high carrier concentration gradient on the border area, which allows for electron and hole diffusion and depletion layer formation. Therefore, space charge of thickness d is created – positive on the n site, because electrons diffuse into p region, and negative on the p site, following the same relation. The resulting potential difference between area p and n is called diffusion voltage, U_d.

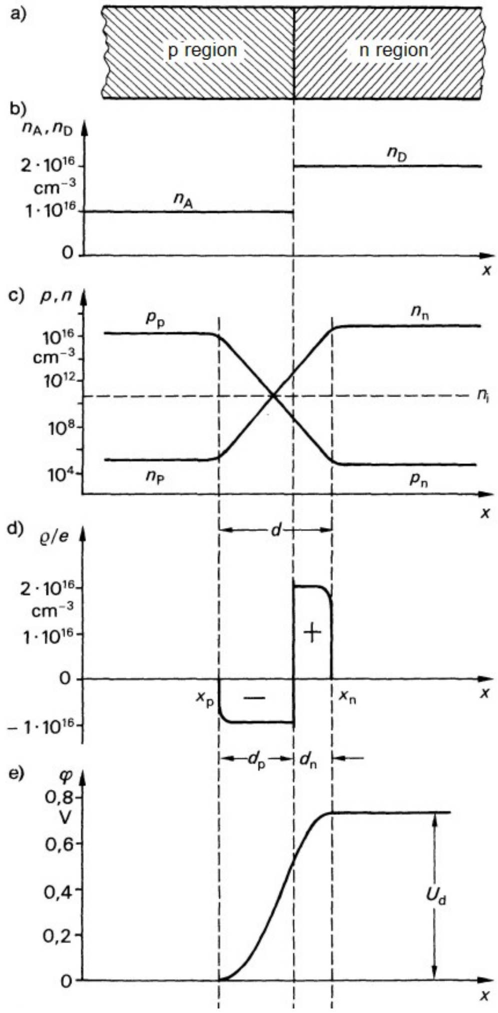


Fig. 2. Asymmetric p-n junction in silicon based material: a) connection between p and n semiconductor type, b) acceptor concentration $n_A = 1 \cdot 10^{16}$ cm^{-3} and donor concentration $n_D = 2 \cdot 10^{16}$ cm^{-3}, c) free carrier concentration, d) volume charge density, e) potential curve [5]

While illuminating p-n junction with the correct wavelength, photons are absorbed and electron-hole pairs are generated (Figure 3a). The field separates both carriers in such a way that electrons reach n region and holes – p region (Figure 3b). It results in a potential difference, polarizing the junction in the conducting direction. The current-voltage characteristic is given by the diode equation, in which I is a current that would flow through p-n junction under the influence of the photoelectric voltage U.

$$I = I_0 [\exp(\frac{eU}{kT}) - 1] \quad (1)$$

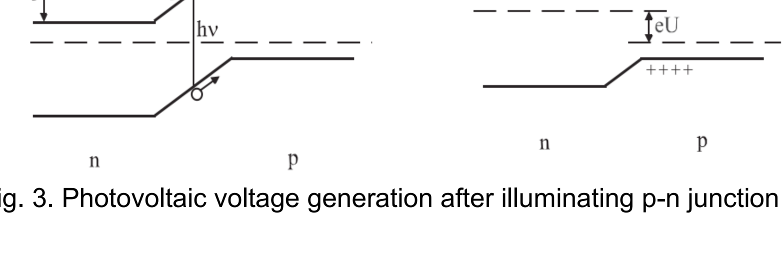


Fig. 3. Photovoltaic voltage generation after illuminating p-n junction [5]

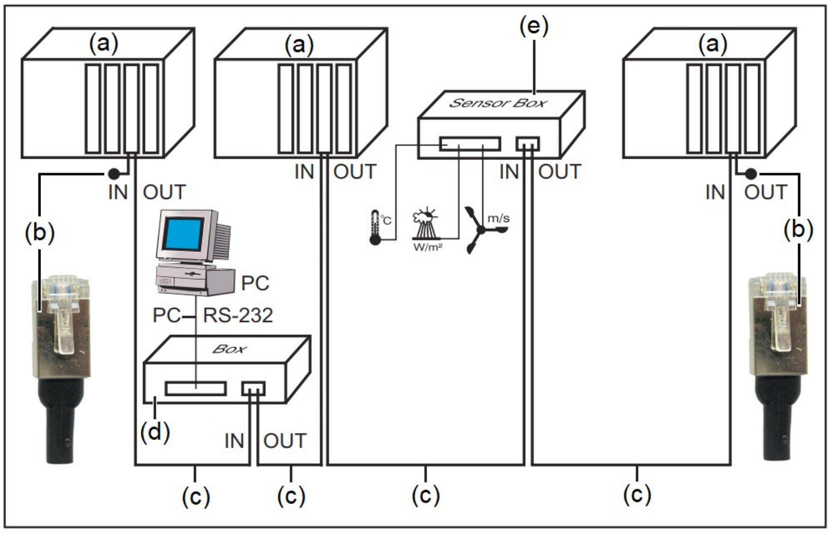
Set of experiments for the study:

A. Drawing up balance sheets based on power and efficiency calculated for the photovoltaic installation

B. Comparing data received from the photovoltaic installation with PV-GIS data

3. Description of the experimental station

The measuring unit consists of 8 photovoltaic modules located on the south-east building facade of Chemistry C Gdańsk University of Technology, inverter and data recorder Fronius Datalogger Card with Sensor Box, which enables data transfer to Fronius Solar.web application. Device sensors register solar radiation, module temperature, ambient temperature, generated electricity, DC and AC voltage and current. The whole system is designed so that it is possible to expand it and add components, as presented in Figure 3.



Rys. 4. a) Inverter equipped with Fronius system, b) terminal resistor, c) data exchange wire, d) data recorder, e) Sensor Box placed in the external encasement [6]

3A. Photovoltaic installation

The measuring unit comprises of 8 silicon based monocrystalline photovoltaic modules BEM-250 Bruk-Bet Solar. Technical specification as well as the current-voltage characteristic are given in Table 1 and Figure 5.

Tab. 1. Electrical and physical properties of BEM-250 Bruk-Bet Solar photovoltaic module [7]

Electrical properties	
Maximum power $[P_{MAX}]$	250 Wp
Short circuit current $[I_{sc}]$	9,20 A
Open circuit voltage $[U_{OC}]$	38,80 V
Maximum power current $[I_{MAX}]$	8,80 A
Maximum power voltage $[U_{MAX}]$	28,45 V
Module efficiency	15,51 %
Power tolerance	0 + 4,99 Wp
Temperature coefficient current	0,03 %/°C
Temperature coefficient voltage	-0,31 %/°C
Temperature coefficient power	-0,39 %/°C
NOCT (800 W/m^2, 20°C, AM 1.5, 1 m/s)	43±2 °C

Physical properties	
Number of solar cells	54
Type	Monocrystalline
Length	1634 mm
Width	986 mm
Thickness	8 mm
Mass	27 kg
Junction box	IP67
Number of bypass diodes	1
Reverse current protection	15 A

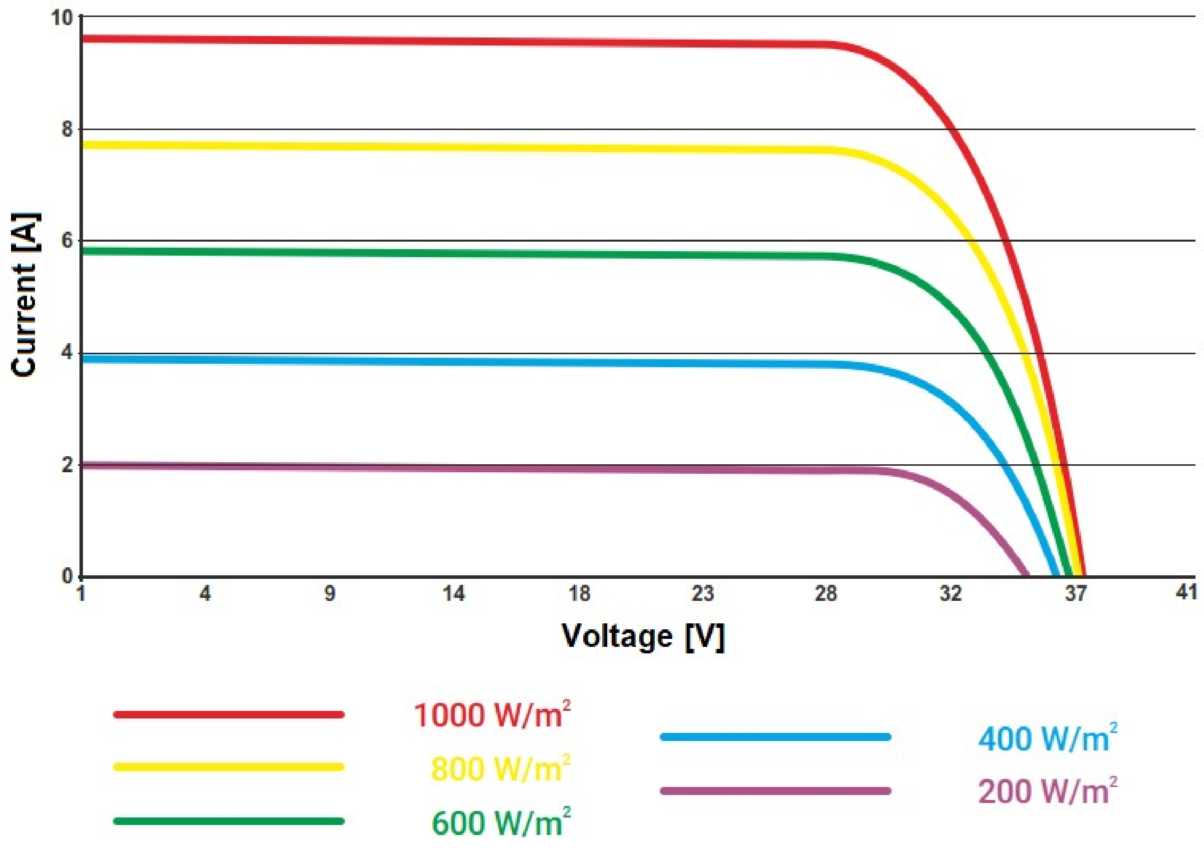


Fig. 5. Current-voltage charecteristic for BEM-250 Bruk-Bet Solar photovoltaic module at different intensity of solar irradiation [7]

3B. Application

Fronius Solar.webb internet application allows for monitoring the condition of photovoltaic installation. The view for installation mounted on Gdańsk University of Technology Chemistry C building facade is seen after choosing “Application commands” in the top left-hand corner and clicking on “Solar.webb” icon. Both of those elements are marked red in Figure 6.

Fig 6. View on the choose menu and application commands

The main application Solar.webb site gives the insight in the ongoing work of photovoltaic installation, meaning its power, energy balance, income and carbon dioxide emission reduction (Figure 7). In addition, overview of the current day and week weather conditions is included.

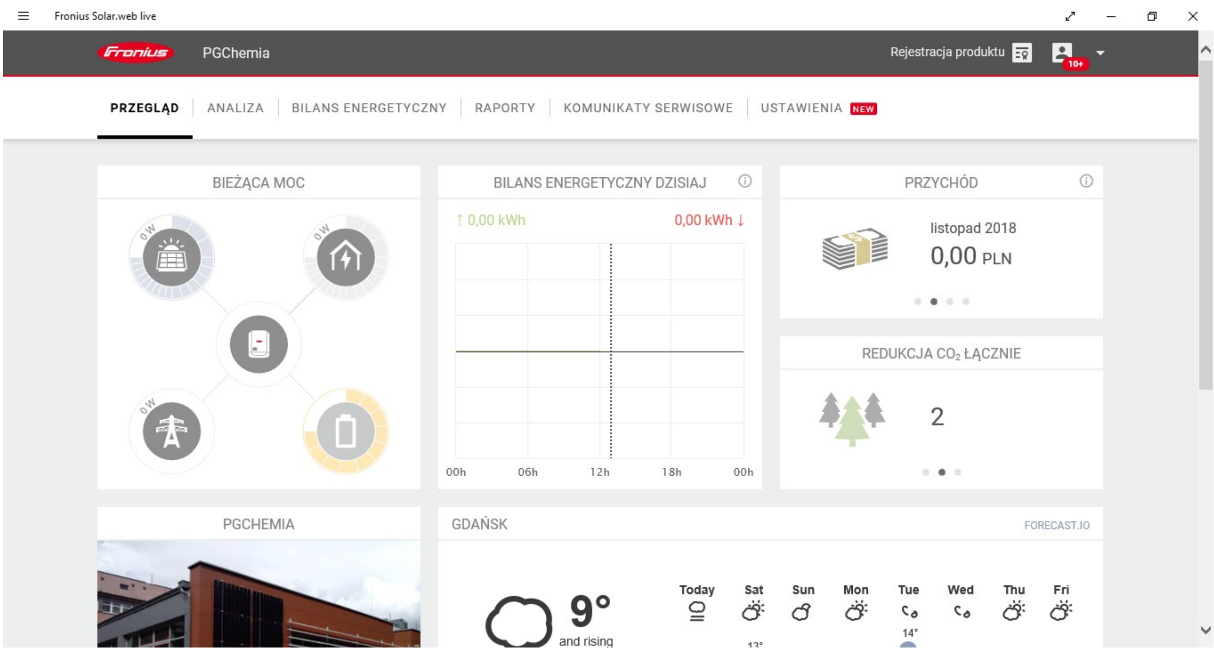


Fig. 7. Main window in Solar.web application

Other bookmarks include data possible to obtain from photovoltaic modules. In “Analysis” bookmark there are sensor card sources for the installation (Figure 8) and more detailed look at the various parameters.

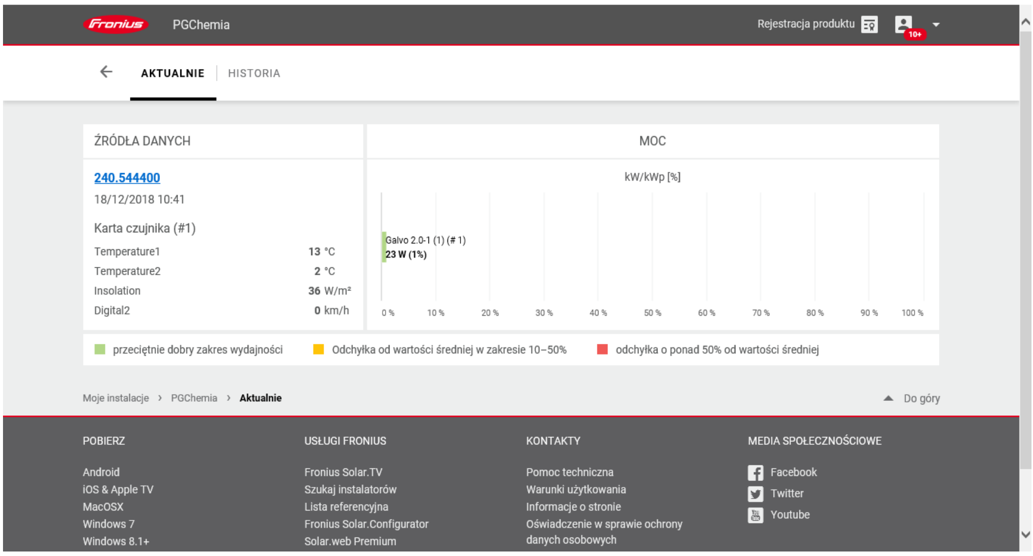
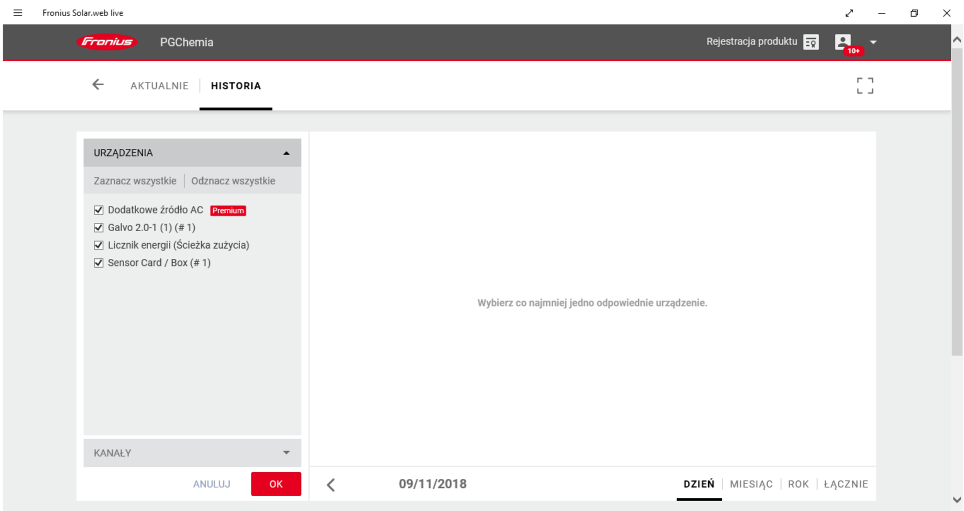


Fig. 8. Current view for photovoltaic installation

Daily, monthly and annual data sets can be obtained by the means of above described application. In order to do that, a desired device and channel need to be chosen (Figure 9). After approving the selected options application plots the relations (Figure 10).

a)



b)

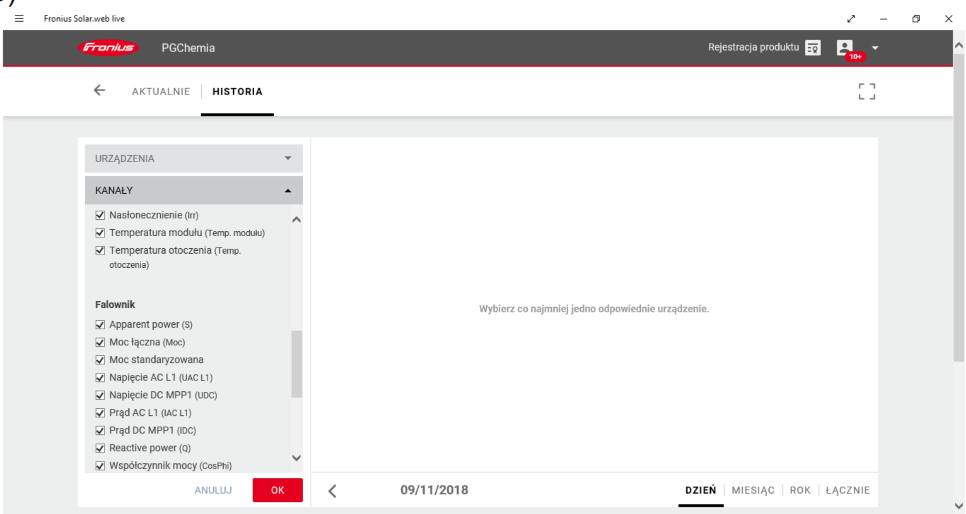


Fig. 9. Channel and device choice for photovoltaic installation

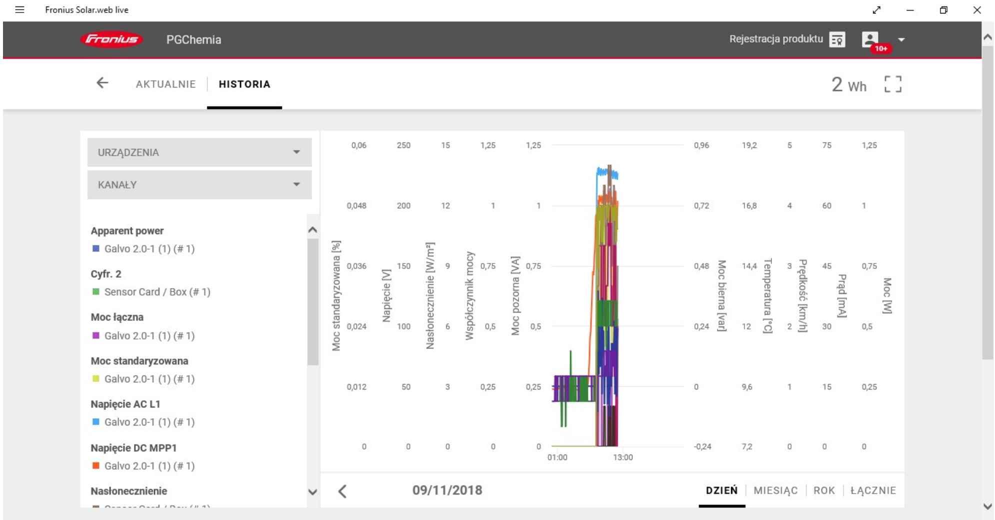
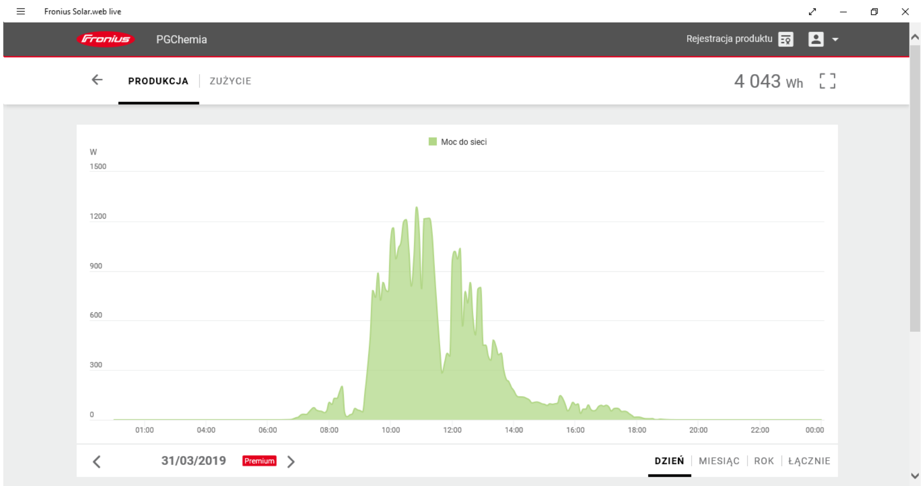


Fig. 10. Graphic representation of the obtained relationships

“Energy balance” bookmark is further broken down into two parts. “Production” bookmark allows to obtain data about energy sent back into the grid in daily, monthly, annual and total summary (Figure 11).

a)



b)

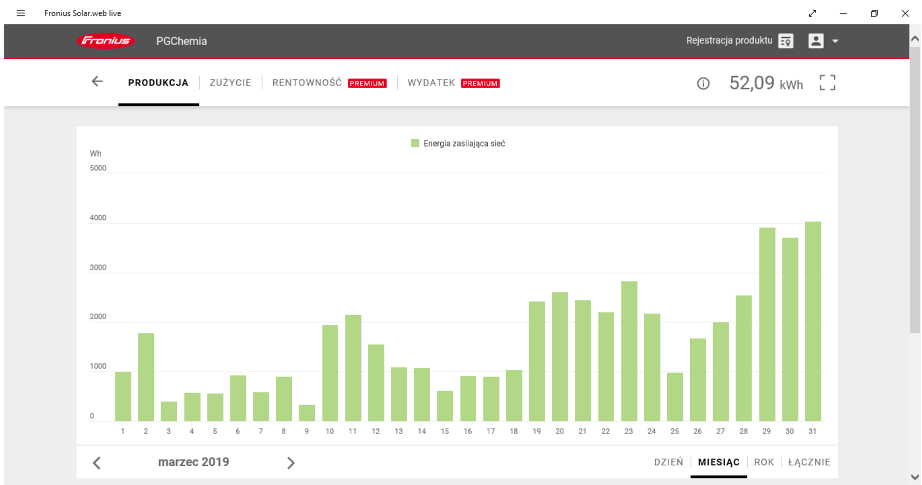


Fig. 11. Energy sent out to grid: a) daily, b) monthly, in April 2019

Additionally, .xlsx reports can be generated, although it should be born in mind that detailed information with a particular time-frame breakdown are generated as “Custom” report type. For daily, weekly and monthly balances data are saved every 5 minutes. There is a possibility to acquire balance for other time-frame, however it needs to be chosen manually in calendar attached to “Generate new report” application option (Figure 12). Data generated for photovoltaic installation include, among others, solar irradiation, ambient temperature, module temperature, energy, voltage and current, which gives the basis to draw up suitable relations. All of the daily, weekly and monthly rapports are in the “Reports” folder on the desktop.

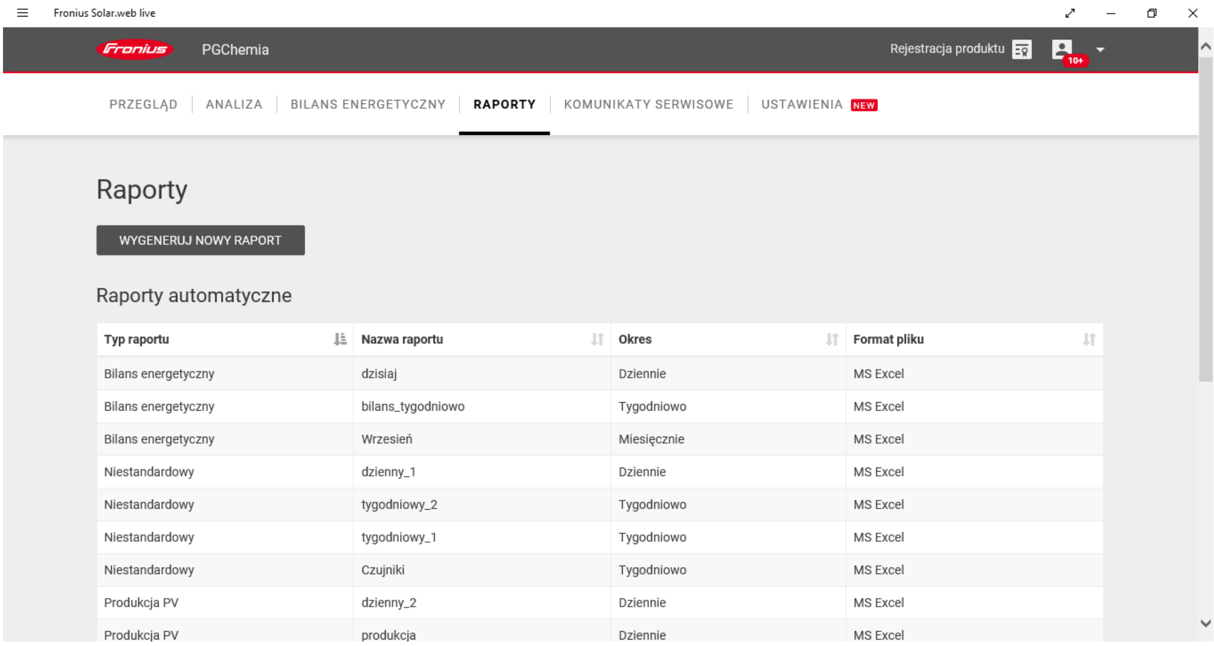


Fig. 12. View for “Reports” bookmark

4. The course of exercise

A. Drawing up balance sheets based on power and efficiency calculated for the photovoltaic installation

In the “Production” bookmark for Solar.web application a daily data set should be considered for a month chosen by the teacher. Determine which day exhibits the highest energy sent out to grid. Next, download reports from “Reports” folder on the desktop – daily report for the above mentioned day with maximum energy yield (Figure 13), as well as weekly and monthly reports.

	A	B	C	D	E	F	G	H	I	J
101	Data i godzina	Nasłonecznienie | Sensor Card / Box	Temperatura modułu | Sensor Card / Bo	Temperatura otoczenia | Sensor Card / Bo	Energia | Galvo 2.0-1 (1) (# 1)	Napięcie AC L1 | Galvo 2.0-1 (1) (# 1)	Napięcie DC MPP1 | Galvo 2.0-1 (1) (# 1	Prąd AC L1 | Galvo 2.0-1 (1) (# 1)	Prąd DC MPP1 | Galvo 2.0-1 (1) (# 1)	
102	[dd.MM.yyyy HH:mm	[W/m²]	[°C]	[°C]	[Wh]	[V]	[V]	[A]	[A]	
103	15.04.2019 08:00	560	20	8	16.99	235.1	249.3	1.2	0.91	
104	15.04.2019 08:05	729.28	18.99	8	13.63	235.7	252	1.14	0.75	
105	15.04.2019 08:10	757	18	8	12.94	234.8	252.2	1.12	0.69	
106	15.04.2019 08:15	815	17	7	11.48	234.9	252.3	1.1	0.62	
107	15.04.2019 08:20	808.99	17.02	8.99	10.98	234.6	254.04	1.07	0.59	
108	15.04.2019 08:25	808	19	8	19.75	234.6	248.1	1.36	1.07	
109	15.04.2019 08:30	827.94	22.02	8.01	30.93	234.4	229.55	1.84	1.8	
110	15.04.2019 08:35	822	24	9	40.01	235.2	214.5	2.24	2.42	
111	15.04.2019 08:40	827	25	9	41.47	234.2	213	2.33	2.54	
112	15.04.2019 08:45	850.19	25.99	8.01	56.97	234.9	203.18	3.03	3.58	
113	15.04.2019 08:50	770	25	9	52.59	235.5	200.8	2.85	3.35	
114	15.04.2019 08:55	855.12	25.98	9	56.41	235.9	207.78	2.99	3.48	
115	15.04.2019 09:00	867	24	9	42.9	236.1	215.9	2.38	2.59	
116	15.04.2019 09:05	866	27	9	61.77	236.6	220.6	3.28	3.57	
117	15.04.2019 09:10	873.02	29.01	9.01	71.3	236.7	234.99	3.7	3.8	
118	15.04.2019 09:15	875	30	10	73.32	236	233.8	3.81	3.94	
119	15.04.2019 09:20	873.02	30	9.99	74.04	236	231.71	3.85	4.01	
120	15.04.2019 09:25	875	30	9	72.13	236.5	232.9	3.73	3.88	
121	15.04.2019 09:30	872	27	8	71.49	236.6	224.8	3.75	4.04	
122	15.04.2019 09:35	868.93	30.01	10	80.51	236.6	230.3	4.15	4.36	
123	15.04.2019 09:40	862	31	10	81.04	236.6	229.9	4.18	4.41	
124	15.04.2019 09:45	855.96	30.02	9	78.72	236.5	230	4.06	4.27	
125	15.04.2019 09:50	852	32	9	79.03	236.3	230.1	4.09	4.3	
126	15.04.2019 09:55	846	34	10	77.79	236.4	230.4	4.05	4.26	
127	15.04.2019 10:00	841.91	33.99	9.99	85.75	236.6	227.85	4.4	4.68	
128	15.04.2019 10:05	833	33	9	94.64	236.4	223.3	4.86	5.26	
129	15.04.2019 10:10	827.89	33	10	95.78	236.6	222.55	4.9	5.32	
130	15.04.2019 10:15	820	33	10	99.65	237.1	217.7	5.1	5.67	
131	15.04.2019 10:20	812	31	10	103	237.2	208.9	5.3	6.22	
132	15.04.2019 10:25	803.93	29.99	9.01	104.66	236.7	205.7	5.34	6.36	
133	15.04.2019 10:30	797	29	10	104.38	236.5	205.8	5.32	6.32	
134	15.04.2019 10:35	787.92	28.01	9.01	103.59	236.1	206.3	5.29	6.26	
135	15.04.2019 10:40	780	29	10	102.38	236.1	206.3	5.24	6.21	
136	15.04.2019 10:45	771	29	10	100.38	236	206	5.18	6.13	
137	15.04.2019 10:50	759.89	28.99	10	100.32	236.2	206.5	5.14	6.08	
138	15.04.2019 10:55	749	28	10	99.51	236.9	206.7	5.08	6	
139	15.04.2019 11:00	738.93	29	11	98.24	237.1	206.9	5.03	5.94	
140	15.04.2019 11:05	732	29	11	97.43	236.7	206.8	4.98	5.88	
141	15.04.2019 11:10	718	29	11	94.68	236.8	206.8	4.89	5.77	
142	15.04.2019 11:15	642.08	28.99	11	85.54	236.8	207.1	4.4	5.16	

Fig. 13. Example of the daily rapport view (15.04.2020)

Draw a graph from the obtained data, representing changes in solar irradiance and energy sent back into the grid (Figure 14) as a function of time. In the second graph plot weekly overview for the same parameters – data should be taken from weekly report (Figure 15).

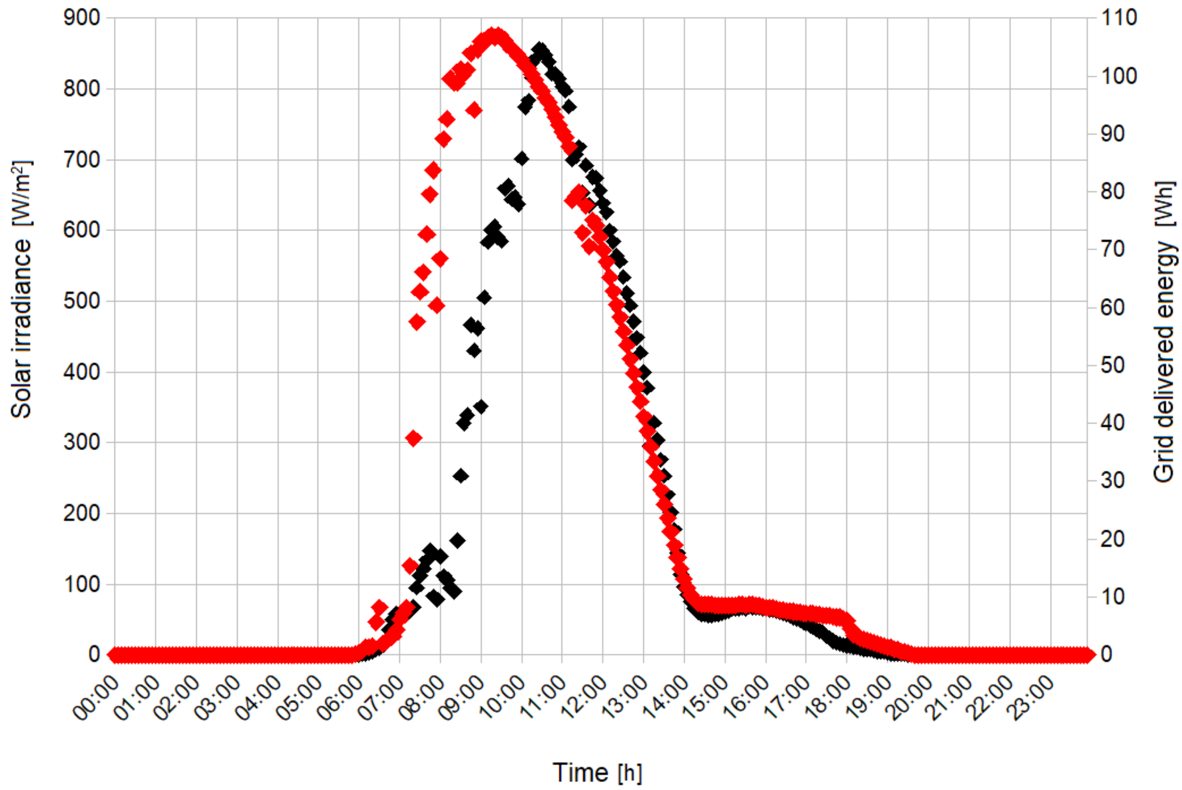


Fig. 14. Solar irradiance (red colour) and energy sent out to grid (black colour) as a function of time. Graph drawn up from daily rapport data for 15.04.2019

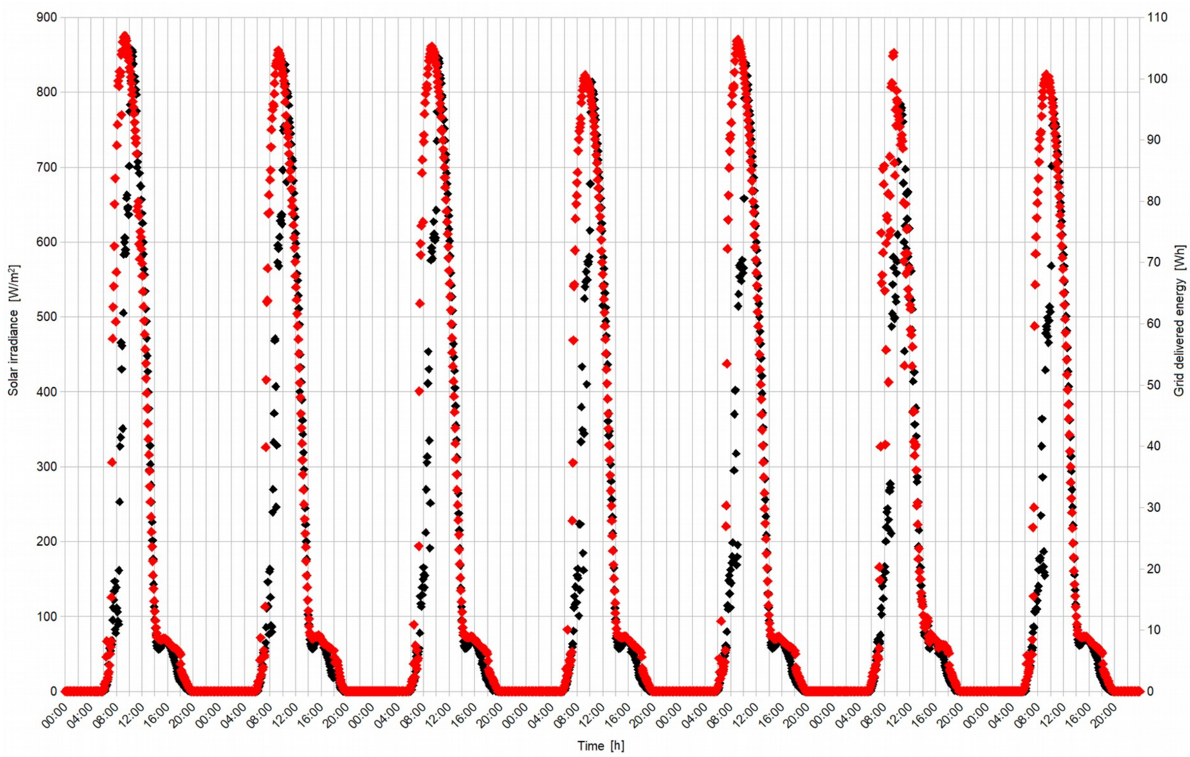


Fig. 15. Solar irradiance (red colour) and energy sent out to grid (black colour) as a function of time. Graph drawn up from weekly rapport data for time-frame 15 – 21.04.2019

Further part of this exercise includes monthly analysis of generated energy, power, as well as efficiency for both PV installation and inverter. Data from monthly report containing daily sums should be plotted as irradiation and generated energy values as a function of time for each day of the month (Figure 16). On the basis of formula (2) calculate the efficiency η for the whole PV installation and present it as graph (Figure 17). Additionally,

$$\eta = \frac{E}{G \cdot S \cdot n} \cdot 100\,\% \tag{2}$$

$$P = I \cdot U \tag{3}$$

$$CR = \frac{P_{DC}}{P_{AC}} \cdot 100\,\% \tag{4}$$

gdzie:

E – generated energy [Wh],

G – energy from solar irradiation [Wh/m^2],

S – area of one PV module [m^2],

.n – number of modules in PV installation [-].

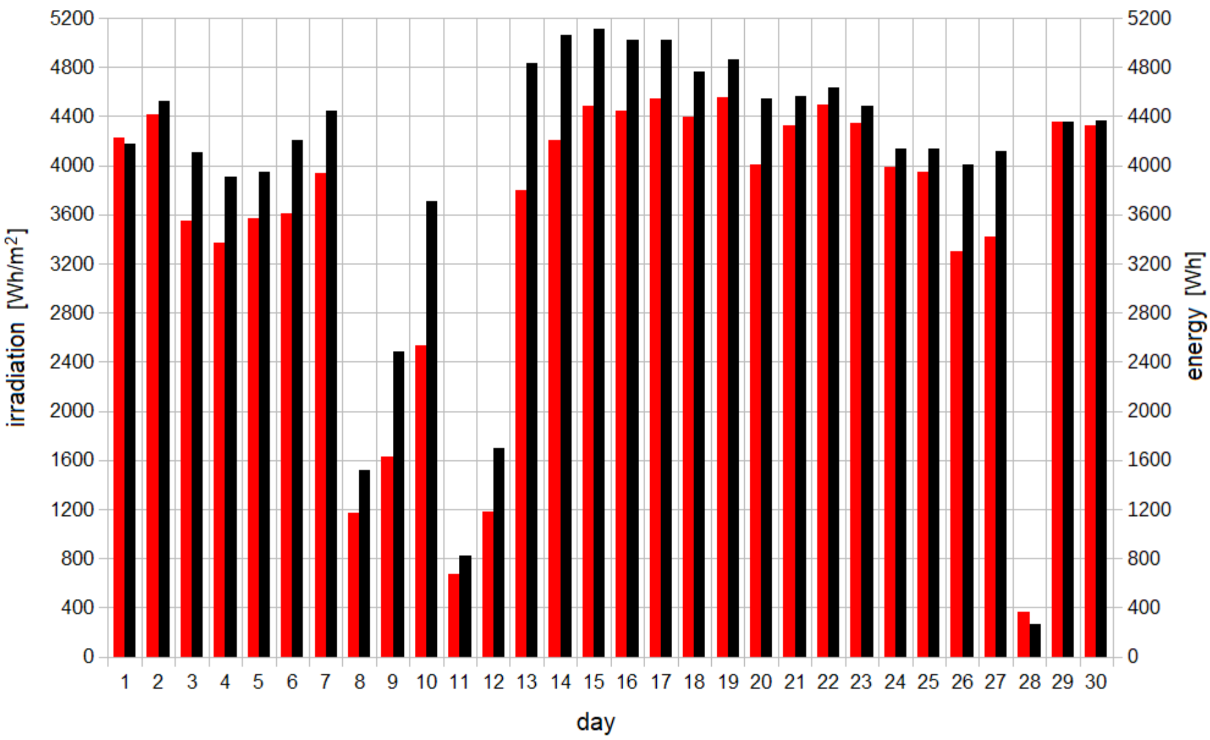


Fig. 16. Solar irradiation (red colour) and energy sent out to grid (black colour) as a function of time. Graph drawn up from monthly report data for April 2019

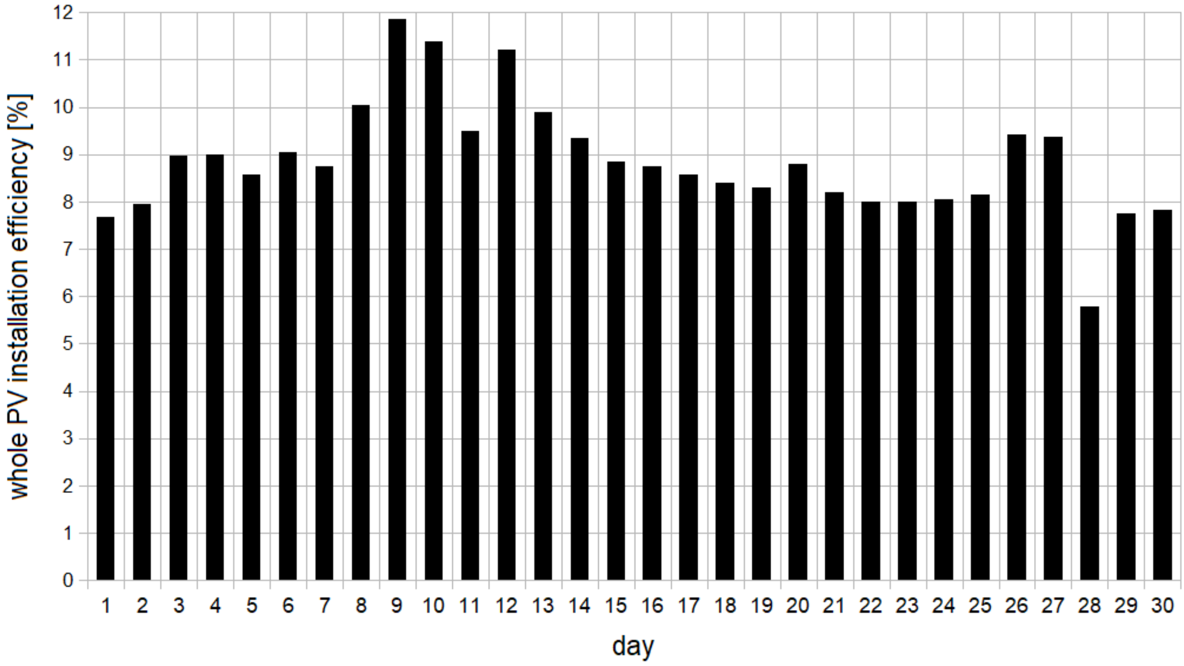


Fig. 17. Whole PV installation efficiency graph drawn up from monthly report data for April 2019

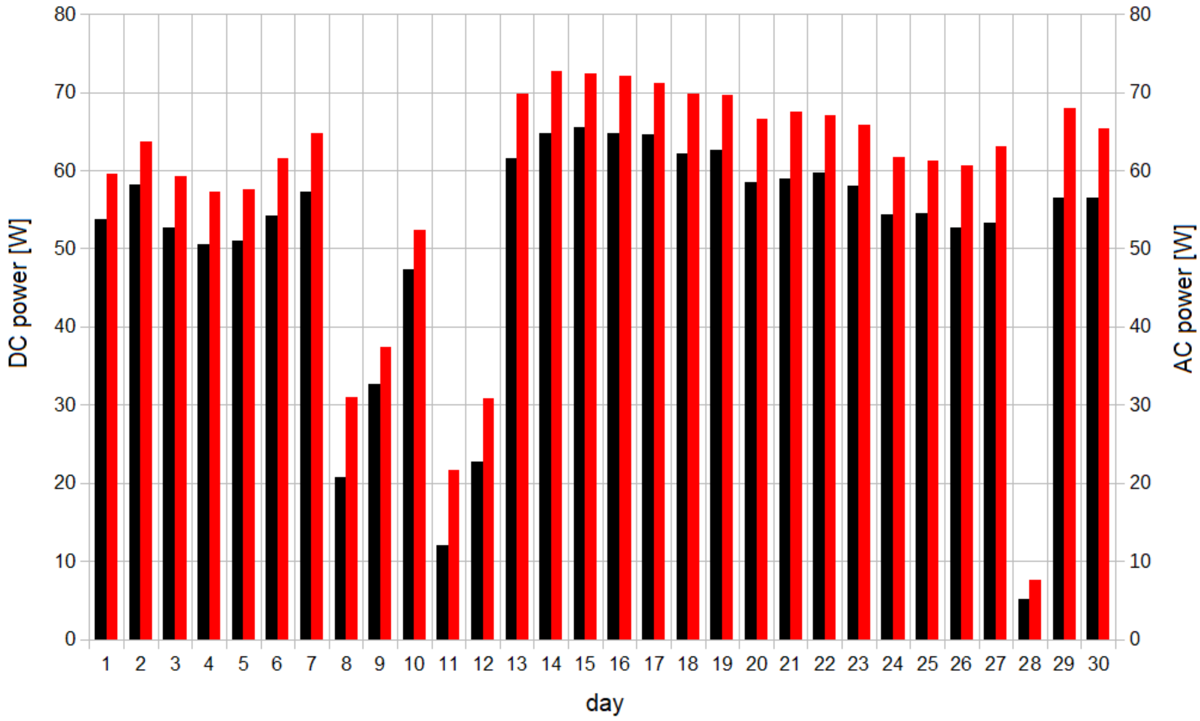


Fig. 18. Power generated on the DC (red colour) and AC site (black colour) drawn up from monthly report data for April 2019

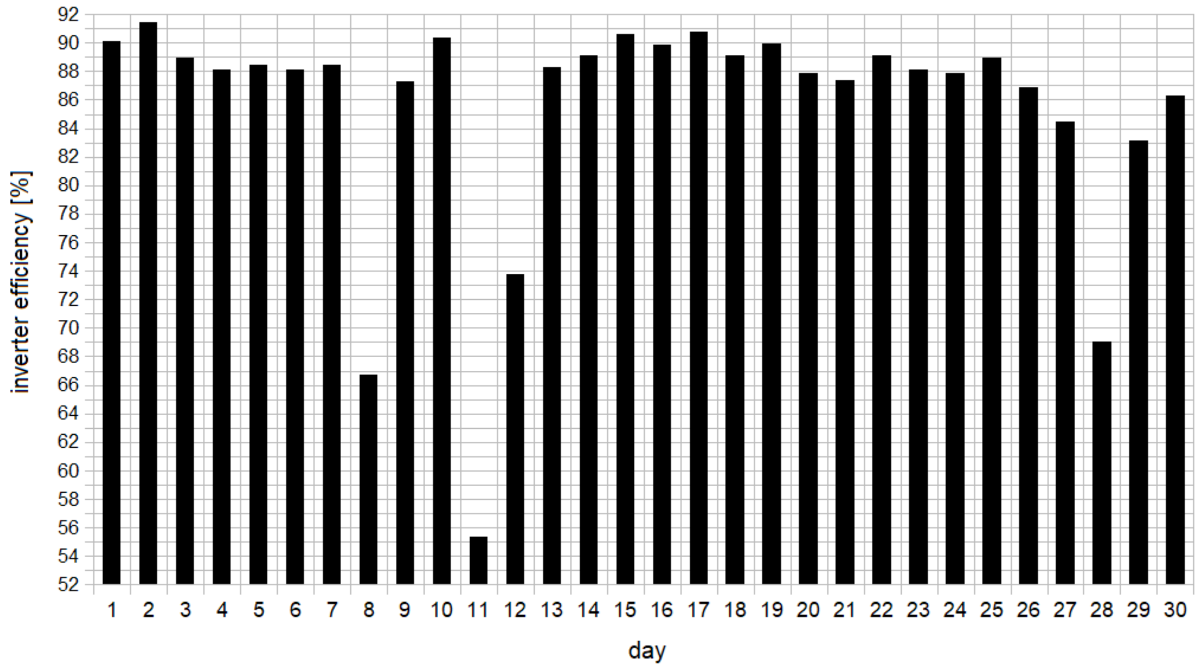


Fig. 19. Inverter efficiency graph drawn up from monthly report data for April 2019

B. Comparing data received from the photovoltaic installation with PV-GIS data

By using the internet geographic information system website for photovoltaic installations (PV-GIS), collect data for average daily and monthly energy possible to generate by the PV installation integrated with Chemistry C building (Figure 20, Figure 21).

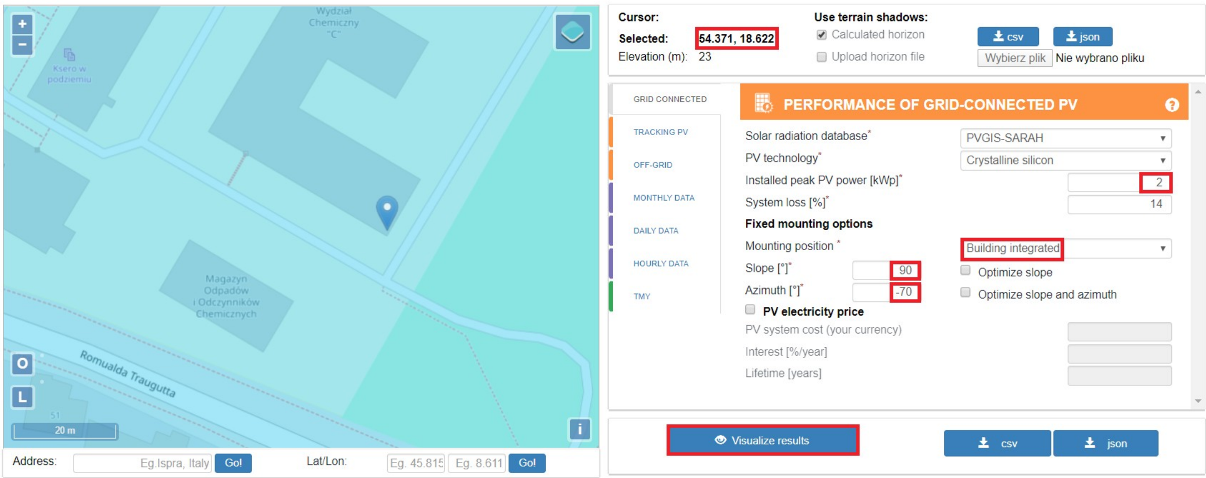


Fig. 20. Parameters entered into the PV-GIS system in order to calculate average monthly energy possible to generate by photovoltaic installation

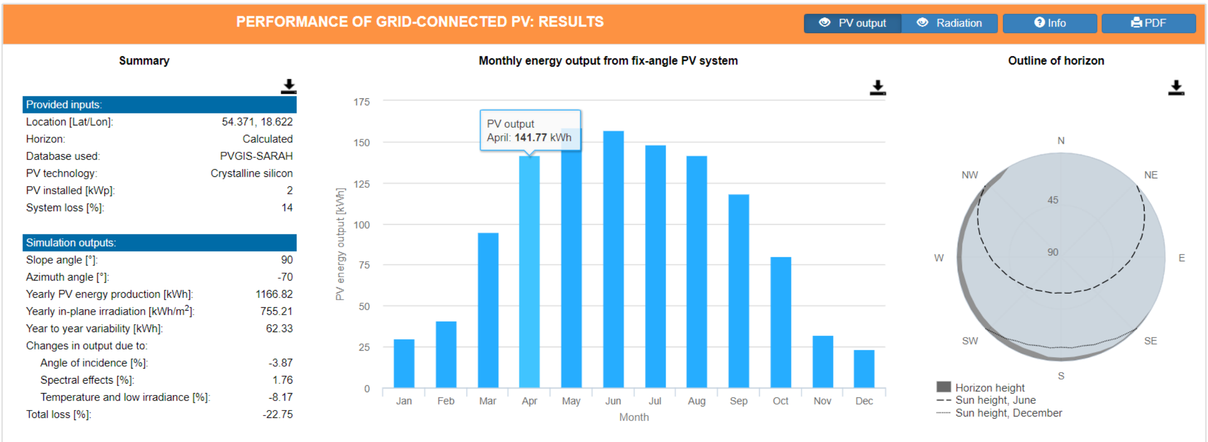


Fig. 21. PV-GIS system data set of average monthly energy possible to generate by photovoltaic installation

Based on data presented in table in Figure 22 assume average monthly solar irradiation for the exact month appointed by the teacher.

Monthly Solar Irradiation

PVGIS Estimates of long-term monthly averages

Location: 54°22'13" North, 18°37'18" East, Elevation: 23 m a.s.l.,

Solar radiation database used: PVGIS-CMSAF

Optimal inclination angle is: 39 degrees
Annual irradiation deficit due to shadowing (horizontal): 0.1 %

Month	H_h	H_{opt}	$H(90)$	I_{opt}	T_{24h}	N_{DD}
Jan	576	1030	1080	68	-2.9	555
Feb	1200	1880	1800	61	-1.8	507
Mar	2900	4130	3550	53	2.6	446
Apr	4520	5480	3860	40	7.4	252
May	5540	5780	3380	25	12.2	127
Jun	5810	5710	3090	17	15.6	55
Jul	5340	5350	3030	20	18.7	11
Aug	4500	5060	3290	33	18.3	41
Sep	3260	4340	3470	48	13.8	181
Oct	1800	2830	2670	60	8.5	342
Nov	688	1180	1200	66	4.8	500
Dec	422	826	907	72	0.2	594
Year	3060	3640	2610	39	8.1	3611

H_h: Irradiation on horizontal plane (Wh/m^2/day)

H_{opt}: Irradiation on optimally inclined plane (Wh/m^2/day)

$H(90)$: Irradiation on plane at angle: 90deg. (Wh/m^2/day)

I_{opt}: Optimal inclination (deg.)

T_{24h}: 24 hour average of temperature (°C)

N_{DD}: Number of heating degree-days (-)

Fig. 22. Monthly change in solar irradiation calculated by the PV-GIS system

By using the value of average daily irradiation H(90), calculate average monthly and daily energy produced by the photovoltaic installation, including 10% all-year-long efficiency. It should be noted that data from the example given below concern 2 kWp installation, and n means the number of days in chosen month.

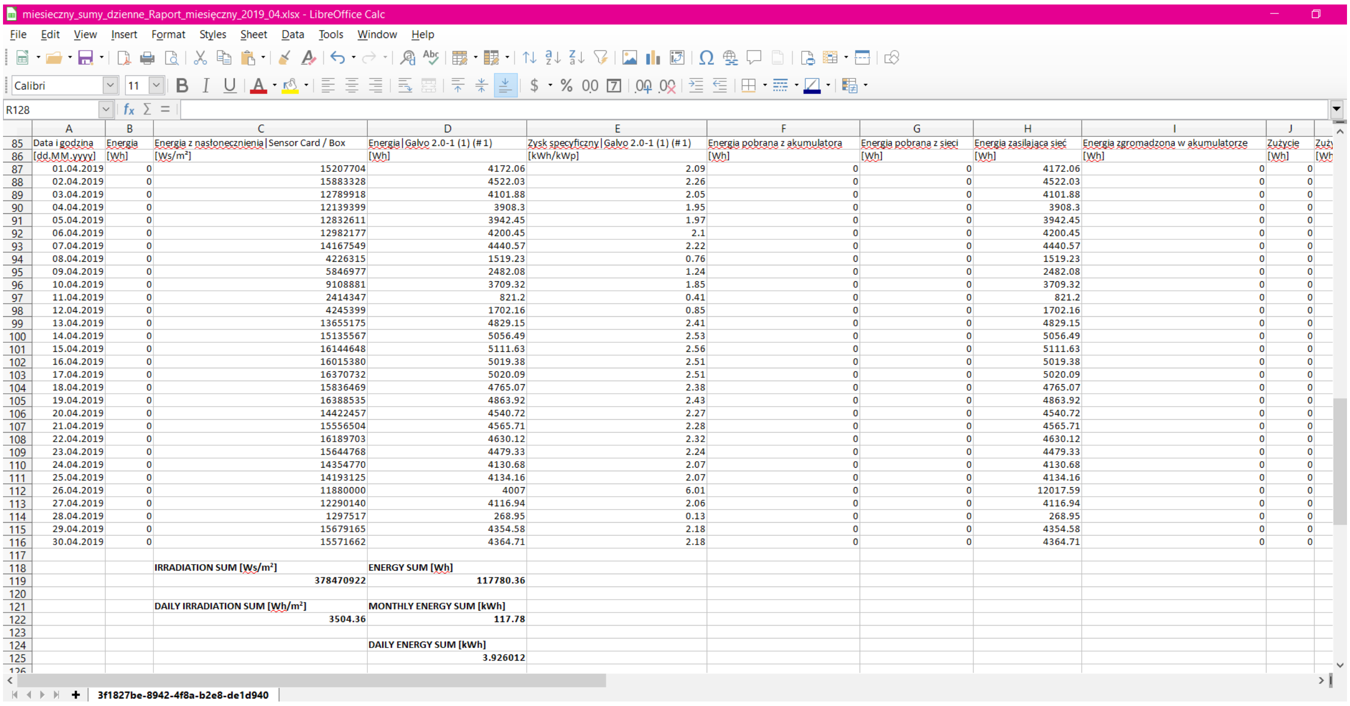
$$E_M = H(90) \cdot S \cdot 30 \cdot 10\,\%$$

$$E_D = \frac{E_M}{n}$$

$$E_M = 3680\,\frac{Wh}{m^2 \cdot day} \cdot 12{,}89\,m^2 \cdot 30\,days \cdot 10\,\% = 142\,305.6\ Wh = 142.31\,kWh$$

$$E_D = \frac{142.31\,kWh}{31} = 4.74\,kWh$$

Then, the same values should be calculated based on data received from the monthly rapport from Fronius application. In order to do that values from the “Irradiation” and “Energy” column should be summed and converted into kWh/m² and kWh (Figure 23).


miesieczny_sumy_dzienne_Raport_miesięczny_2019_04.xlsx - LibreOffice Calc

	A	B	C	D	E	F	G	H	I	J
85	Data i godzina	Energia	Energia z nasłonecznienia | Sensor Card / Box	Energia | Galvo 2.0-1 (1) (# 1)	Zysk specyficzny | Galvo 2.0-1 (1) (# 1)	Energia pobrana z akumulatora	Energia pobrana z sieci	Energia zasilająca sieć	Energia zgromadzona w akumulatorze	Zużycie
86	[dd.MM.yyyy]	[Wh]	[Ws/m²]	[Wh]	[kWh/kWp]	[Wh]	[Wh]	[Wh]	[Wh]	[Wh]
87	01.04.2019	0	15207704	4172.06	2.09	0	0	4172.06	0	0
88	02.04.2019	0	15883328	4522.03	2.26	0	0	4522.03	0	0
89	03.04.2019	0	12789918	4101.88	2.05	0	0	4101.88	0	0
90	04.04.2019	0	12139399	3908.3	1.95	0	0	3908.3	0	0
91	05.04.2019	0	12832611	3942.45	1.97	0	0	3942.45	0	0
92	06.04.2019	0	12982177	4200.45	2.1	0	0	4200.45	0	0
93	07.04.2019	0	14167549	4440.57	2.22	0	0	4440.57	0	0
94	08.04.2019	0	4226315	1519.23	0.76	0	0	1519.23	0	0
95	09.04.2019	0	5846977	2482.08	1.24	0	0	2482.08	0	0
96	10.04.2019	0	9108881	3709.32	1.85	0	0	3709.32	0	0
97	11.04.2019	0	2414347	821.2	0.41	0	0	821.2	0	0
98	12.04.2019	0	4245399	1702.16	0.85	0	0	1702.16	0	0
99	13.04.2019	0	13655175	4829.15	2.41	0	0	4829.15	0	0
100	14.04.2019	0	15135567	5056.49	2.53	0	0	5056.49	0	0
101	15.04.2019	0	16144648	5111.63	2.56	0	0	5111.63	0	0
102	16.04.2019	0	16015380	5019.38	2.51	0	0	5019.38	0	0
103	17.04.2019	0	16370732	5020.09	2.51	0	0	5020.09	0	0
104	18.04.2019	0	15836469	4765.07	2.38	0	0	4765.07	0	0
105	19.04.2019	0	16388535	4863.92	2.43	0	0	4863.92	0	0
106	20.04.2019	0	14422457	4540.72	2.27	0	0	4540.72	0	0
107	21.04.2019	0	15556504	4565.71	2.28	0	0	4565.71	0	0
108	22.04.2019	0	16189703	4630.12	2.32	0	0	4630.12	0	0
109	23.04.2019	0	15644768	4479.33	2.24	0	0	4479.33	0	0
110	24.04.2019	0	14354770	4130.68	2.07	0	0	4130.68	0	0
111	25.04.2019	0	14193125	4134.16	2.07	0	0	4134.16	0	0
112	26.04.2019	0	11880000	4007	6.01	0	0	12017.59	0	0
113	27.04.2019	0	12290140	4116.94	2.06	0	0	4116.94	0	0
114	28.04.2019	0	1297517	268.95	0.13	0	0	268.95	0	0
115	29.04.2019	0	15679165	4354.58	2.18	0	0	4354.58	0	0
116	30.04.2019	0	15571662	4364.71	2.18	0	0	4364.71	0	0
117										
118			IRRADIATION SUM [Ws/m²]	ENERGY SUM [Wh]						
119			378470922	117780.36						
120										
121			DAILY IRRADIATION SUM [Wh/m²]	MONTHLY ENERGY SUM [kWh]						
122			3504.36	117.78						
123										
124				DAILY ENERGY SUM [kWh]						
125				3.926012						

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Fig. 23. Calculation example for April based on data received from Fronius application

All of the obtained results – from Fronius application, PV-GIS system and calculations, are presented in table with a distinction being made between 2 kWp and 1 kWp installation.

Tab. 2. Average daily (H(90)) irradiation, maximum daily (E_D) and monthly (E_M) energy produced by photovoltaic installation in April

	For 2 kWp installation			**For 1 kWp installation**		
	Fronius	*PV-GIS*	*Calculations*	*Fronius*	*PV-GIS*	*Calculations*
H(90) [Wh/(m²·day)]	3504,36	3860,00	3860,00	3504,36	3860,00	3860,00
E_M [kWh]	117,78	141,77	142,31	58,89	70,89	71,16
E_D [kWh]	3,93	4,73	4,74	1,96	2,36	2,37

5. Literature

[1] Ewa Klugmann-Radziemska, Fotowoltaika w teorii i praktyce, Wydawnictwo BTC, Warszawa-Legionowo 2009.

[2] Eugeniusz Klugmann, Ewa Klugmann-Radziemska, Alternatywne źródła energii. Energetyka fotowoltaiczna, Wydawnictwo Ekonomia i Środowisko, Białystok 1999, s. 75-158.

[3] Ewa Klugmann-Radziemska, Technologiczny postęp w fotowoltaice, Czysta Energia, 5, 2014.

[4] Paul Hersch, Kenneth Zweibel, Basic Photovoltaic Principles and Methods, Solar Energy Research Institute, Colorado 1982.

[5] Piotr Grygiel, Henryk Sodolski, Laboratorium Konwersji Energii, Wydział Fizyki Technicznej i Matematyki Stosowanej, Politechnika Gdańska, 2014, s. 25-41.

[6] Fronius Datamanager. Galvo – Symo – Primo – Eco. Monitorowanie instalacji. Fronius.

[7] Product card BEM-250 Bruk-Bet Solar.