

Design of system model and program for estimation of annual PV energy production: a comparative study

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Abstract

Suitability evaluation of a location for power generation plant installation requires long-term measurements and calculations. Since the energy production values foreseen in the project process of the solar power plant directly affect the return period of the project cost, it is of great importance to make the calculations correctly. In this study, a model and program were designed to find the closest estimation values. Energy production values are estimated for 54 kWh solar power plant (SPP) in Balıkesir using designed model. It is important that the SPP consists of two groups with different angles, directions and capacities in terms of comparing the accuracy of the calculation. The developed model used the hourly meteorological data and catalog values to Energy production calculations. The model allows making calculations for all the angles of the sun and the characteristic data of the system. The developed program was compared with energy production results of PVGIS (Photovoltaic Geographical Information System) programs. As a result of analysis, it has been observed that more realistic and closer results were produced by means of the designed program. The advantage of this program is that more parameters of the photovoltaic (PV) system can be monitored compared to the other programs.

Keywords: Solar energy, Matlab/Simulink, PVGIS, Sarah 2, prediction of SPP energy generation.

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Yıllık PV enerji üretiminin tahmini için sistem modeli ve programın tasarımı: karşılaştırmalı bir çalışma

Öz

Bir yerin elektrik üretim tesisi kurulumuna uygunluğunun değerlendirilmesi, uzun vadeli ölçümler ve hesaplamalar gerektirir. Güneş enerjisi santralinin proje sürecinde öngörülen enerji üretim değerleri, proje maliyetinin geri dönüş süresini doğrudan etkilediği için hesaplamaların doğru yapılması büyük önem arz etmektedir. Bu çalışmada en yakın tahmin değerlerini bulmak için bir model ve program tasarlanmıştır. Tasarlanan model kullanılarak Balıkesir ilindeki 54 kWh güneş enerjisi santrali (GES) için enerji üretim değerleri tahmin edilmiştir. GES'in farklı açılara, yönlere ve kapasitelere sahip iki gruptan oluşması hesaplamanın doğruluğunun karşılaştırılması açısından önemlidir. Geliştirilen model, saatlik meteorolojik verileri ve katalog değerlerini Enerji üretimi hesaplamalarında kullanmıştır. Model, güneşin tüm açılarının ve sistemin karakteristik verilerinin hesaplanmasına olanak sağlar. Geliştirilen program PVGIS (Photovoltaic Geographical Information System) programlarının enerji üretim sonuçları ile karşılaştırılmıştır. Yapılan analizler sonucunda tasarlanan program sayesinde daha gerçekçi ve yakın sonuçlar üretildiği görülmüştür. Bu programın avantajı diğer programlara göre fotovoltaik (FV) sistemin daha fazla parametresinin izlenebilmesidir.

Anahtar kelimeler: Güneş enerjisi, Matlab/Simulink, PVGIS, Sarah 2, GES enerji üretim tahmini

1. Introduction

Solar energy is a clean, safe, free, environmentally friendly and inexhaustible source of energy. Solar photovoltaic technology is one of the most important renewable energy generation sources. The efficiency of the PV system depends on climatic factors such as solar radiation, ambient temperature and the condition of the solar modules, such as age, soiling, etc.

In measuring the efficiency of photovoltaic solar energy systems, it is important in which conditions the solar panel receives how much solar radiation and how much energy is produced from the inverter output.

The most important input parameter affecting energy production is the irradiation to hit the panel. Effective radiation is dependent on the latitude-longitude, tilt angle and mounting direction, which vary according to the mounting location of the panel [1,2].

Meteorological data and radiation values of the point determined for the installation of the system can be measured, as well as data can be obtained from institutions and companies that measure with professional devices. However, theoretical radiation values can be calculated for bright and cloudless sky conditions. Copper et al. [3] compared mathematical models for estimating solar irradiance for Australia. After obtaining meteorological radiation data, the effective irradiation coming to the surface can be calculated. Shen et al. [4] studied on the program created with Simulink to interpolate radiation data, calculated several quantities related to the position of the sun, and estimated the solar radiation on surfaces with variable or fixed orientation. Tina et al.

[5] compared PV plant performance models considering climate effects. Wind speed affected the panel temperature and efficiency. Al-Ghussain et al. [6] investigate the significant effects of ambient temperature, wind speed, dust accumulation, and cleaning frequency for four different PV panel types in Jordan, Egypt, and Tunisia using precise ground-based meteorological measurements.

For the specified coordinates, the radiation coming to the surface can be calculated by taking into account the motion of the earth around the sun and the sun angle during the day, the slope and direction angle of the mounted solar panel system. Karafil et al. [2] examined the effects of panel inclination angle on energy production in Bilecik province. Rustemli et al. [7] made a comparison of solar energy system with solar tracking system and fixed mounting. Beyoglu [8] compared energy productions of fixed and 2-axis tracking photovoltaic solar energy systems in Balikesir province. About [9] studied on the most important parameters such as solar angles and prepared a MATLAB code to calculate these angles at any time and location. After that he analyzed the pattern of solar angles and the solar path. Jazayeri et al. [10] studied a simulation model for calculating the position of the sun in the sky and the angle of incidence angle of the sunlight beams on the surface of solar panels with any tilt angle, located at any geographical location on the Earth's surface.

The efficiency and material specifications of solar energy systems directly affect the amount of energy produced. Solar cells are the basic components to convert solar radiation into electrical energy. The efficiency of the panels used in the system varies according to the material used in the panel construction and technology, ambient temperature and the age of the panel [5]. Humada et al. [11] presented a new approach to the extraction of a single-diode five-parameter model and its performance evaluation. Brano et al. [12] worked on an adaptive approach based on different topologies of artificial neural networks for forecasting the power generating of photovoltaic modules.

Yildiran et al. [13] developed and simulated a photovoltaic cell single-diode detailed model. They determined the model parameters based on datasheet values and analyzed the model. Anand et al. [14], Vinod et al. [15] studied modelling and simulation of photovoltaic module using Matlab/Simulink. Bouraiou et al. [16] studied the modeling and simulation of photovoltaic modules and array based on a one- and two-diode model using Matlab/Simulink software. Lidaighbi et al. [17] presents a new simple and accurate hybrid method for estimating the five parameters of the single diode model based on the remarkable points and the information from the PV data sheet. Vinod et al. [18] a single diode equivalent circuit model is presented with the step-by-step detailed simulation of a PV solar module under Matlab/Simulink environment.

For a specific location, if the mounting angle and direction, panel technical characteristics and nominal power value are known, approximate values of the amount of electrical energy to be produced can be calculated. Paid and free programs have been developed to make these calculations more accurate and practical. Real meteorological data are used in these programs for the desired location from various meteorology data banks. Huld et al. [19] examined the effect of a different solar radiation data on Photovoltaic Geographical Information System (PVGIS) program calculations. Beyoglu et al. [20] compared different energy production estimation programs with the actual energy production data of a solar power plant established in Balikesir province. Tian et al. [21] worked on a detailed performance model for photovoltaic systems. Neamt et al. [22] worked to provide the simplest way for estimating the energy production of a

photovoltaic system anywhere on the earth. Abdelhayt [23] studied on a MATLAB Simulink model that constructed a detailed representation of the PV solar system connected with either to the local low voltage grid or to the national high voltage grid. Mohanty et al. [24] compared the performance of different MPPT methods that are used in a solar PV system and also advocates a new MPPT technique which offers better performance than the existing ones. Parra et al. [25] reviewed the currently available PV performance models with regard to accuracy and also compliance with datasheet specifications and examined measurement conducted on PV arrays of four different technologies at a PV plant.

In this study, a model was prepared to estimate the closest values to the output of real systems. The energy production data of 54 kWh solar power plant installed in Balıkesir were used to compare the prepared model with different energy production forecast programs.

In this program, the production calculation has been made using real meteorology data taking into account the location of the system, mounting angle and catalog values. PVGIS-Sarah 2 data was used as meteorological data. The results of program was observed that the program gave more realistic and closer results according to the others.

Nomenclature

V_{PV}	Output voltage of PV	β	PV tilt angle
V_{oc}	Open circuit voltage	Z_s	Solar zenith angle
I_{sc}	Short circuit current	α_s	Solar azimuth angle (NO)
K_v	PV voltage temperature coefficient	α_m	PV azimuth angle
K_i	PV current temperature coefficient	G	Solar irradiance
T_{cell}	Solar cell temperature	G_b	Beam irradiance
T_{amb}	Ambient temperature	G_d	Diffuse irradiance
V_{wind}	Speed of wind	G_r	Reflection irradiance
φ	Latitude	GHI	Global horizontal irradiation
θ	Incidence of angle	DHI	Diffuse horizontal irradiation
η	Efficiency of inverter	R_b	Ratio of tilted/horizontal irr.
γ_s	Solar altitude angle	X_{sky}	View factor of sky
δ	Declination angle	X_{grd}	View factor of ground
ω	Solar hour angle	ρ_p	Albedo of the ground
P_{max}	Maximum power of PV	b_0	IAM coefficient
		IAM	Incidence angle modifier

2. Energy production forecast program

Energy generation forecast program consists of solar position calculation, surface irradiation calculation, PV system and inverter efficiency calculation modules. The block diagram of the PV system model is given in Figure 1. The properties of the modules will be explained in subsections. Designed program needs hourly meteorology data, geographic coordinates with montage info of SPP and some system information for calculation. Output of the program gives the position of the sun, the radiation coming to the surface, the panel and inverter output energy production values hourly.

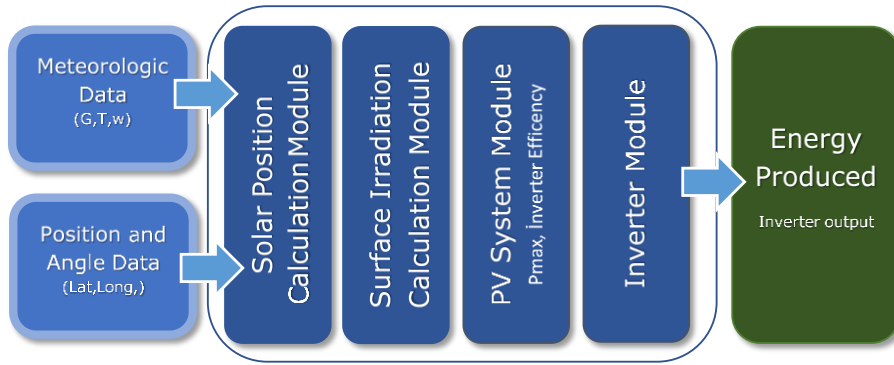


Figure 1. Block diagram of the designed program modules

The designed model uses single diode model with five parameters of PV cells as shown in Figure 2 [18]. The model calculates the maximum power (P_{max}) value for the ambient temperature and radiation values. For this, it uses the V-I and P-V characteristic curves of the panel and catalog values.

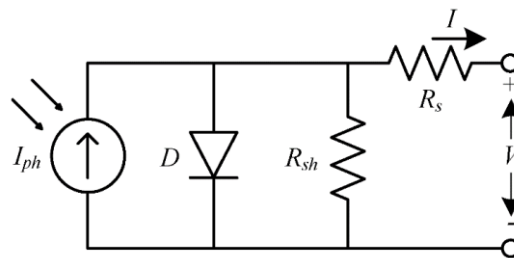


Figure 2. PV panel single diode model

The effective value of solar radiation on the panel changes with the angle of incidence. The incident angle modifier (IAM) is defined as the ratio of light transmitted at the angle of incidence to normal incidence. IAM was added to the model for obtaining more accurate results. Inverter efficiency is given as a constant in datasheet, but actually the efficiency decreases rapidly at low power values. Therefore, the inverter efficiency module was added to the system to estimate more realistic results at low power values. PV system model Simulink diagram is given in Figure 3.

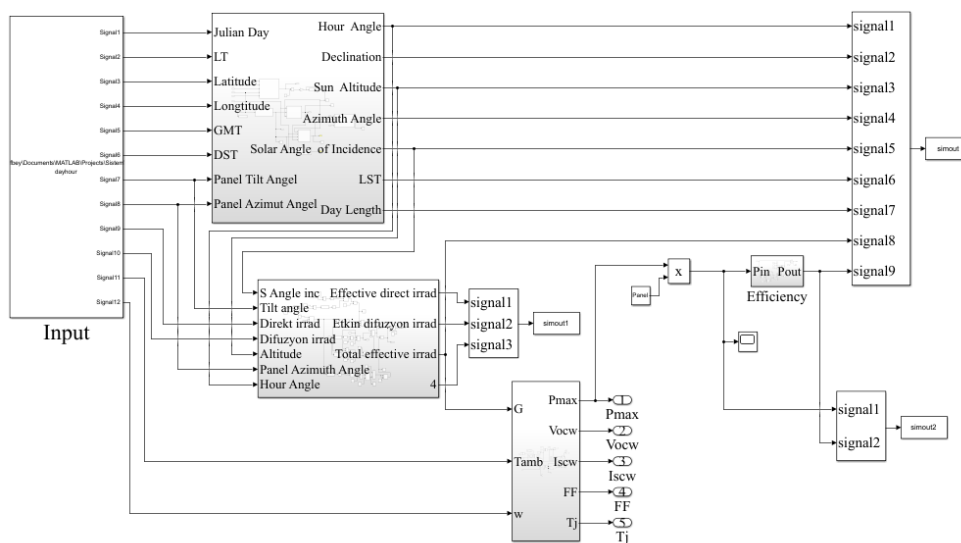


Figure 3. The Simulink diagram of the designed program modules

The model block diagram is shown in Figure 4.

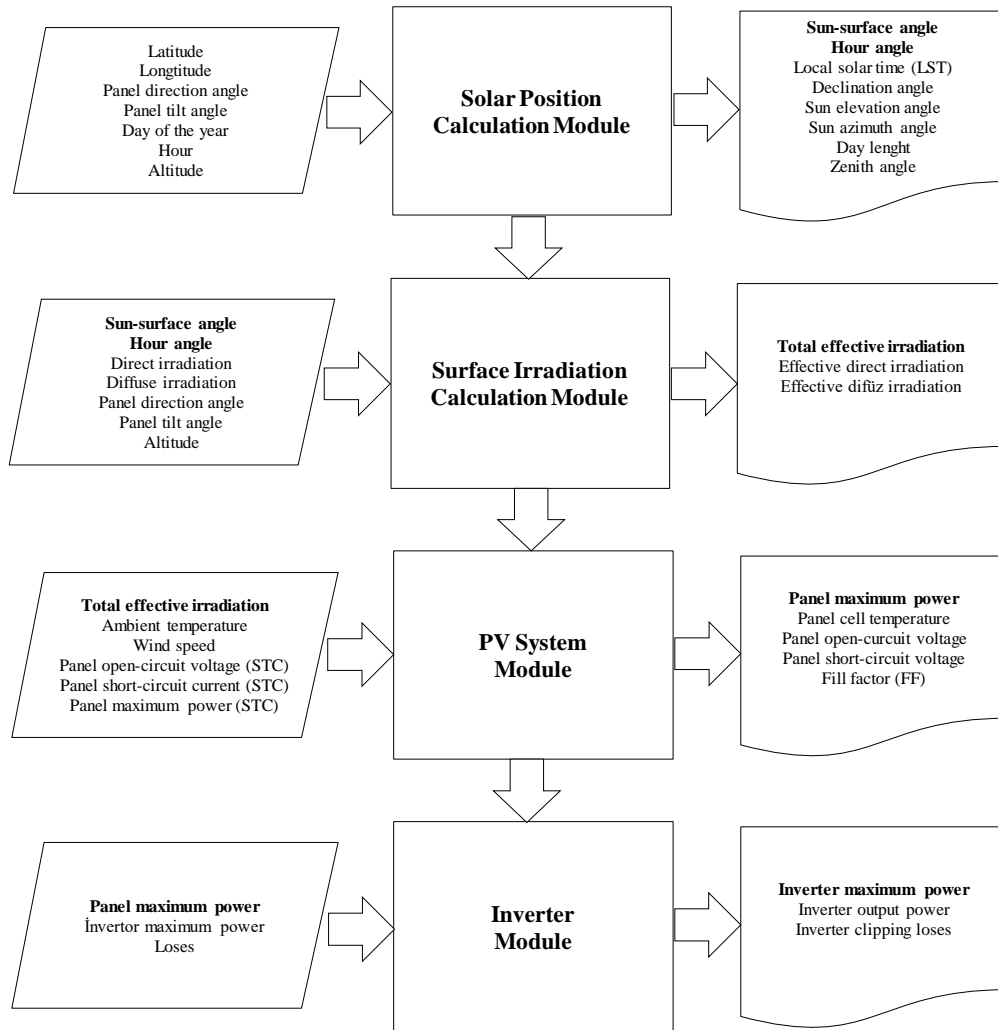


Figure 4. Model block diagram

2.1. Sun position and angle calculation module

For SPP coordinates, the effective value of the radiation coming to the surface can be calculated by the sun angle, the slope and direction angle of the solar panel system. The angles are shown in Figure 5.

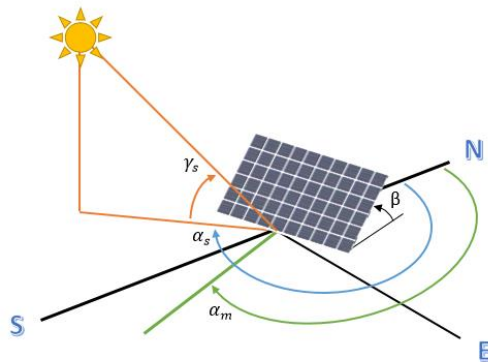


Figure 5. PV panel directions and angles

Solar and panel angles calculation module uses the angle of incidence with latitude, longitude, date, time, sun azimuth and elevation angles, direction and tilt angle of the panel to calculate solar angles. In addition to angle of incidence is also calculated, hour angle, local solar time (LST) and day length. Simulink diagram for this module is shown in Figure 6.

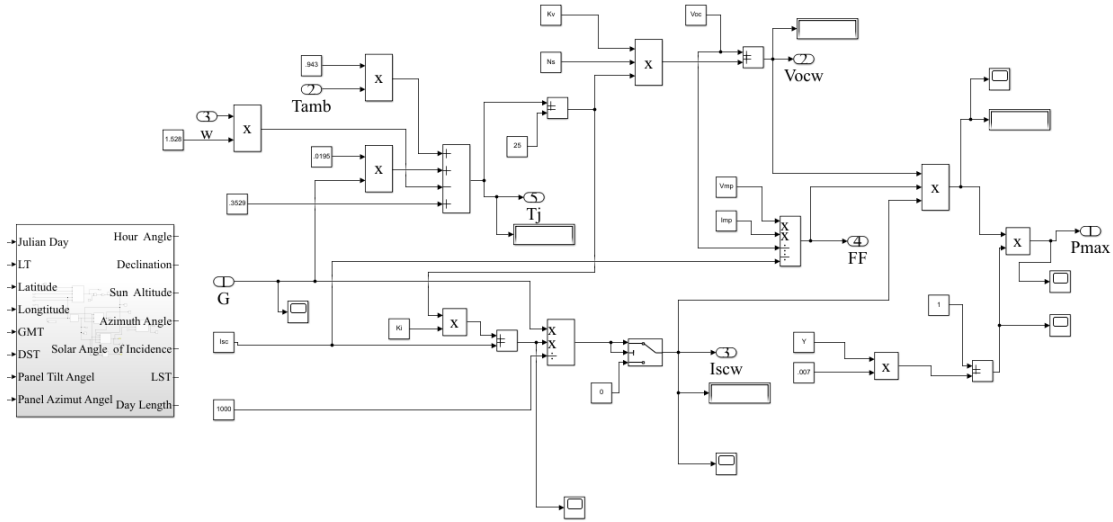


Figure 6. Solar and panel angles calculation module

Sun elevation angle (γ_s) is calculated using the latitude (φ) of the location, the declination angle (δ) and the solar hour angle (ω). It is written as follows [10];

$$\gamma_s = \sin^{-1} (\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega) \quad (1)$$

Sun azimuth angle (α_s) is calculated using the sun elevation angle (γ_s), the latitude (φ) of the location, the declination angle (δ) at the daily and the solar hourly angle (ω). It is given in Eq.2 [10];

$$\begin{cases} \alpha_s = 180 - \cos^{-1} (\cos \alpha_s) & \text{if } \sin \alpha_s < 0 \\ \alpha_s = 180 + \cos^{-1} (\cos \alpha_s) & \text{if } \sin \alpha_s > 0 \end{cases} \quad (2)$$

where,

$$\cos \alpha_s = (\sin\varphi \sin\gamma_s - \sin\delta) / \cos\varphi \cos\gamma_s \quad (3)$$

$$\sin \alpha_s = \cos\alpha_s \sin\omega / \cos\gamma_s \quad (4)$$

Sun surface angle (θ) is calculated using the panel slope (β), solar zenith angle (Z_s), solar azimuth angle (α_s) and panel azimuth angle (α_m). It is given in Eq.5 [10].

$$\theta = \cos^{-1} [\cos \beta \cos Z_s + \sin \beta \sin Z_s \cos (\alpha_s - \alpha_m)] \quad (5)$$

2.2. Surface active irradiation calculation module

The effective irradiance calculation module uses the parameters direct and diffusion solar radiations coming to the earth and the angle of incidence on the surface.

The total radiation is equal to sum of the direct, diffusion and reflection radiation values. It is given in Eq.6 [1].

$$G = G_b + G_d + G_r = (GHI - DHI)R_b + DHI X_{sky} + GHI \rho_p X_{grd} \quad (6)$$

where G_b , G_d , G_r , GHI , DHI , X_{sky} , X_{grd} , ρ_p and R_b are the beam irradiance, the diffuse irradiance, the reflection irradiance, global horizontal irradiance, diffuse horizontal irradiance, the view factor of panel to sky, the view factor of panel to ground, the albedo of the ground, the ratio of tilted irradiance and horizontal irradiance, respectively.

The effective solar irradiance on the panel surface changes with the angle of incidence and more realistic results. IAM was used to obtain more realistic results in the module as given in Eq.7 [26]. IAM can be written as follows;

$$IAM = 1 - b_0 \left(\frac{1}{\cos\theta} - 1 \right) \tag{7}$$

Where θ is the incidence angle of solar beam radiation on the PV surface, b_0 is a constant of the IAM. Figure 7 shows the IAM changes with the incidence angle.

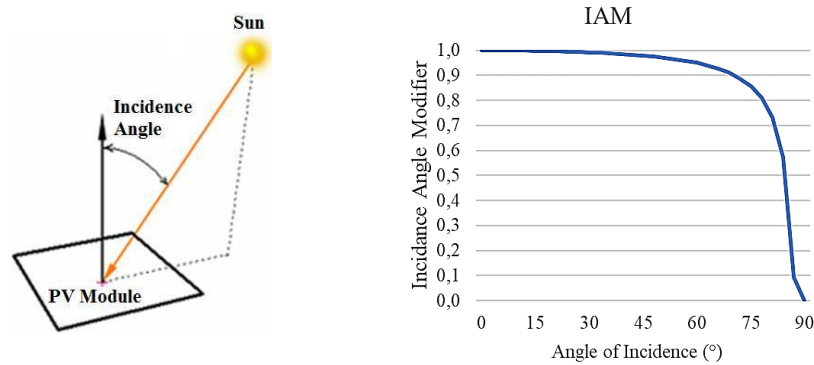


Figure 7. IAM correction factor Simulink diagram of the surface effective irradiance calculation module is given in Figure 8.

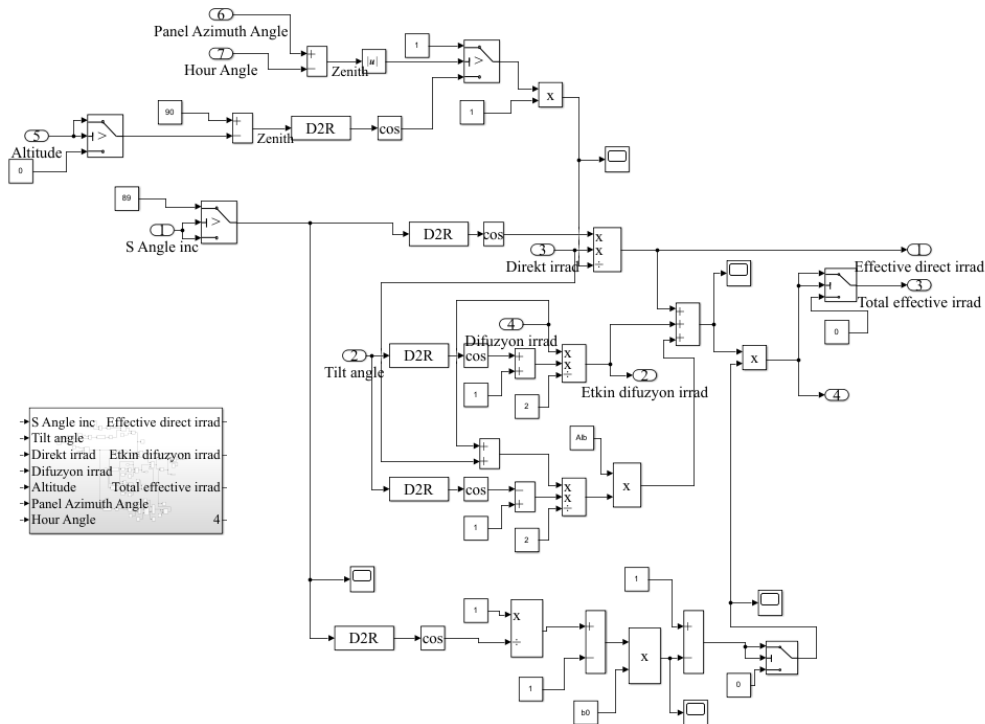


Figure 8. Surface effective irradiation calculation module

2.3. PV system module

Photovoltaic panel's specifications and characteristic curves are given in the datasheets. These curves change at different ambient temperatures and irradiance values. The PV system module is used to calculate the maximum power point correctly in all conditions. The short circuit current, open circuit voltage, fill factor and maximum power point are calculated as follows;

$$I_{scw} = [I_{sc} + K_i(T_{amb} - T_{ref})] \frac{G}{G_{ref}} \quad (8)$$

$$V_{ocw} = V_{oc} + K_v(T_{amb} - T_{ref}) \quad (9)$$

$$FF = \left(\frac{V_{opt} I_{opt}}{V_{oc} I_{sc}} \right) \quad (10)$$

$$P_{max} = FF V_{ocw} I_{scw} \quad (11)$$

The maximum power of the panel at standard test conditions (STC), K_i current and K_v voltage coefficients are given in the datasheet. The short-circuit current and open-circuit voltage values are calculated for different temperature and radiation values by using current and voltage coefficients. They are given in Eq.8 and Eq.9 [14,27]. The fill factor (FF) is a parameter determines the maximum power in conjunction with V_{oc} and I_{sc} at a solar cell. FF is given in Eq.10 [27].

The maximum power point P_{max} is calculated in Eq.11 by using FF , short-circuit current and open-circuit voltage [27]. System datasheet information used in the SPP is given in Section 4 as Table 2.

Solar panel cell temperature T_{cell} is calculated with ambient temperature T_{amb} , amount of radiation G and wind speed V_{wind} . The power value is inversely proportional to the cell temperature. The wind speed increases the efficiency as it contributes to the cooling of the panel. The correlation for calculating the cell temperature is given in Eq.12 [28]. Radiation and temperature variation graphics of the maximum power point are shown in Figure 9. The cell temperature is calculated as follows:

$$T_{cell} = 0.943 T_{amb} + 0.0195 G - 1.528 V_{wind} + 0.3529 \quad (12)$$

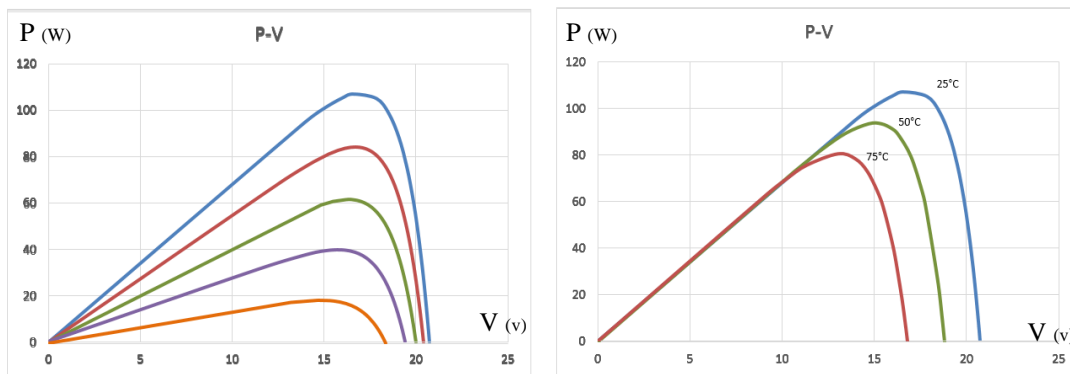


Figure 9. Variation of PV system Pmax value with radiation and temperature

Simulink diagram of the module to calculate the maximum power point is shown in Figure 10.

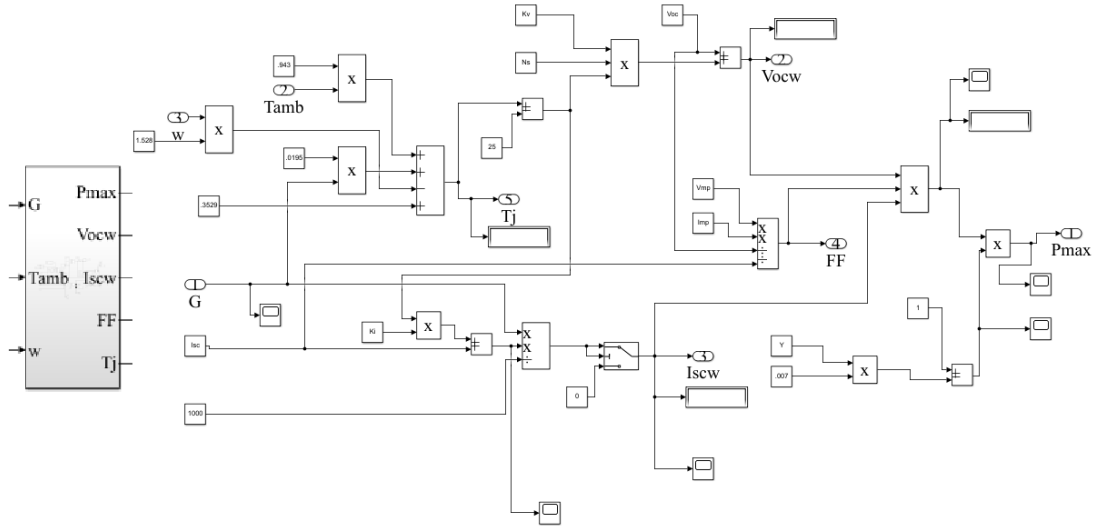


Figure 10. PV system Pmax calculation module

2.4. Inverter efficiency module

The inverters used in the PV system are designed to convert the DC energy produced by the panels into AC energy with the high efficiency. The system follows the maximum power point under all conditions. The fixed losses of the system are also important during low irradiate and the efficiency of the system decreases rapidly. Figure 11 shows the efficiency curve of the inverter used in the system and the efficiency curve is calculated with the module shown in Figure 12. The efficiency of the inverter can be written as follows:

$$\eta = \frac{\eta_{norm}}{\eta_{ref}} \left(-0.016138 \xi - \frac{0.0059}{\xi} + 0.9858 \right) \quad (13)$$

where,

$$\xi = \frac{P_{DC}}{P_{DC0}} \quad (14)$$

$$P_{DC0} = \frac{P_{AC0}}{\eta_{norm}} \quad (15)$$

Inverter efficiency is calculated by considering the input power at the optimum operating conditions and the input instantaneous power. They are given Eq.13, Eq.14 and Eq.15 [29].

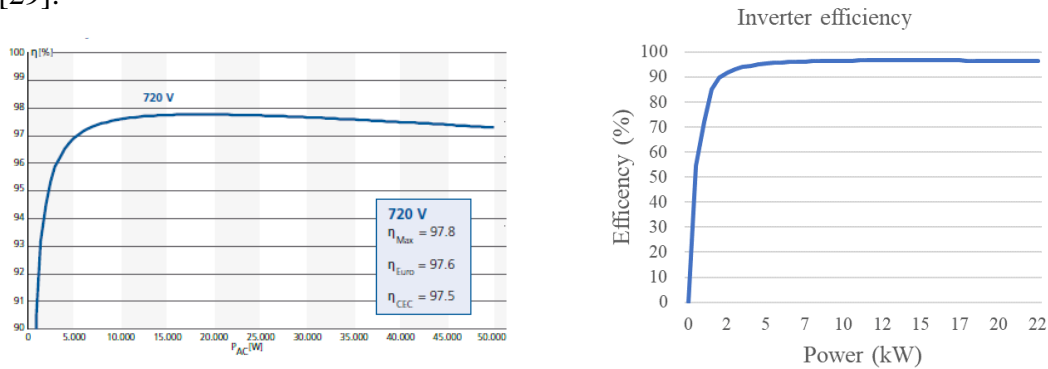


Figure 11. The inverter efficiency curves of the catalog and module

The module that calculates the inverter efficiency and system losses is shown in Figure 12.

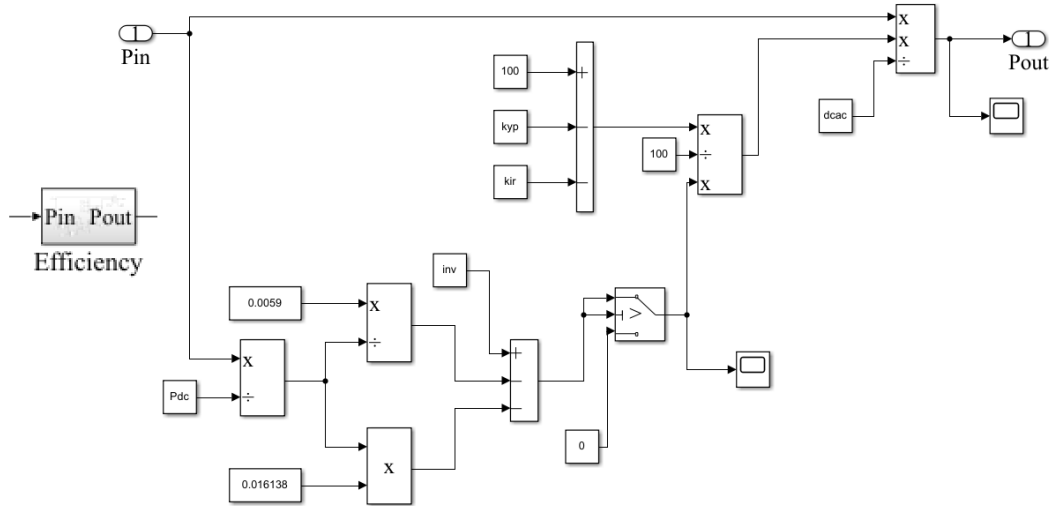


Figure 12. Inverter and system efficiency calculation module

3. Meteorological data

The meteorological data for the calculations can be measured or obtained from institutions and companies that measure with professional devices.

The irradiation, ambient temperature and wind speed data are used panel energy production calculations. Hourly average solar radiation, temperature and wind speed data are obtained from the SARAH 2 database. Monthly total irradiation and the irradiation peak values given in Table 1.

Table 1. Meteorological data sample (Total value)

PVGIS-SARAH 2	TOTAL VALUE		PEAK VALUE	
	BEAM (DIRECT) IRRADIANCE (W/m ²)	DIFFUSE IRRADIANCE (W/m ²)	BEAM (DIRECT) IRRADIANCE (W/m ²) *	DIFFUSE IRRADIANCE (W/m ²) *
JANUARY	43.311	27.361	822	570
FEBRUARY	76.105	41.158	869	321
MARCH	93.894	57.087	948	471
APRIL	178.104	76.351	892	444
MAY	160.921	84.433	927	477
JUNE	211.293	77.477	934	475
JULY	238.461	81.950	923	469
AUGUST	169.645	78.963	885	430
SEPTEMBER	154.416	65.078	890	410
OCTOBER	120.697	49.501	903	332
NOVEMBER	95.291	39.834	863	274
DECEMBER	73.766	31.207	817	250
TOTAL	1.615.903	710.399	948	570

2016, 2017, 2018, 2019,2020 data of SARAH 2 was used in the program for calculations.

4. Program data

The energy production of a SPP established in Balıkesir Province was compared with different energy production forecast programs. The SPP is located in Balıkesir (39.6N 27.9E) and consists of two groups. The each group has 108 polycrystalline panels and one inverter. As shown in Figure 13, it is directed at 59° (Group 1) and 239° (Group 2) symmetrical angles and mounted on 17° angled roof.

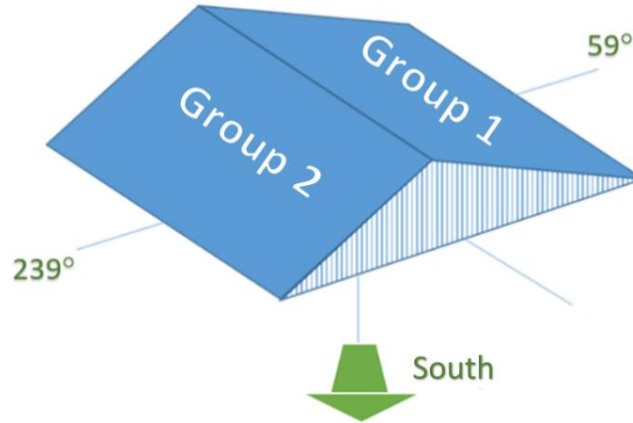


Figure 13. Roof view of the real system

The real SPP system catalog information is given in Table 2.

Table 2. System catalog information

SYSTEM INFORMATION			
PV DATASHEET		INVERTER DATASHEET	
Model	BYD 250P6-30	Model	POWADOR 33.0 TL3
Voc	38 V	Operation Voltage	200 V-950 V DC
Vmp	30,40 V	Max Input Current	3X34 A
Isc	8,98 A	Efficiency	98%
Imp	8,22 A		
Pmax	250 W		
Efficiency	15,37%		

The inverter used in the system is a 3 MPPT, IGBT switched, self-changing transformerless on-grid inverter.

Circuit diagram of a system with two inverters is shown in Figure 14.

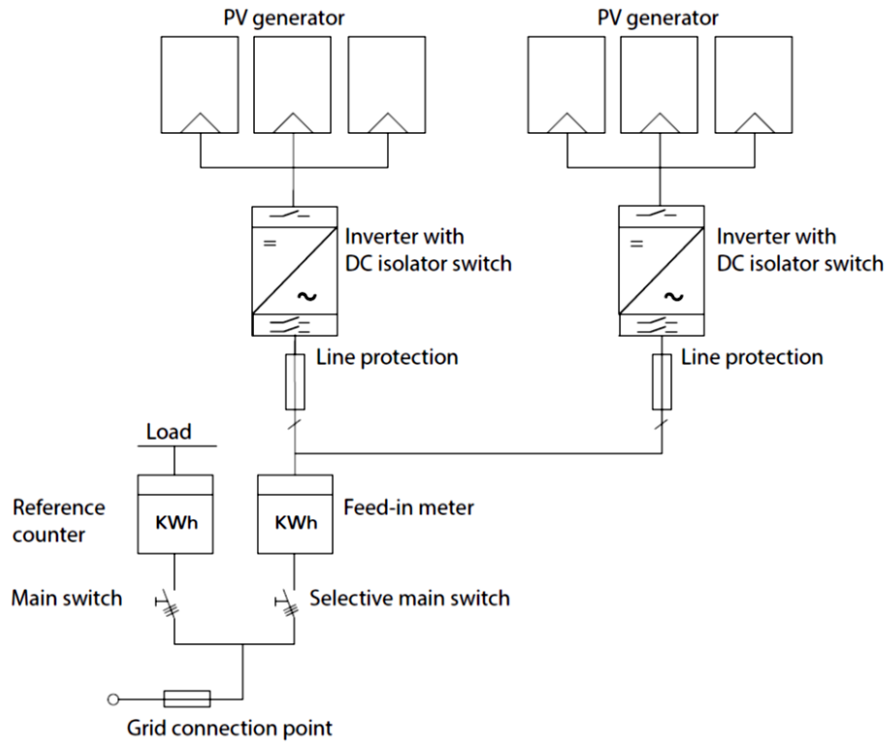


Figure 14. Circuit diagram of a system with two inverters

4.1 PVGIS Program Calculation

PVGIS program is a free solar energy calculation program prepared by the European Commission. The program is accessible at https://re.jrc.ec.europa.eu/pvg_tools/en/. The PVGIS program calculates the produced energy by using the system installed power, panel technology, location, total system losses, mounting type, angle of the panel and meteorology data for the location.

The real SPP energy production is calculated with PVGIS program and 2016-2020 period monthly energy production is given in Table 3.

4.2 Program Calculation

The characteristic parameters of photovoltaic panels are given in the datasheets with numerical values and curves. These curves changes with ambient temperature and radiation values. The PV system program calculates the operating curves of the panel in the datasheet and determines the maximum power point correctly in all conditions.

The real SPP energy production values were compared with results of developed program, the PVGIS program. The comparison results are given in Table 3.

Table 3. Comparison of the designed program and PVGIS Results

2016	GROUP 1 (59°)					GROUP 2 (239°)				
	SPP	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]	%	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]
JANUARY	564	731	29%	796	41%	922	1.236	34%	1.208	31%
FEBRUARY	1.144	1.138	-1%	1.257	10%	1.799	1.769	-2%	1.762	-2%
MARCH	2.216	2.202	-1%	2.293	3%	2.725	2.827	4%	2.653	-3%
APRIL	3.230	3.217	0%	3.410	6%	3.872	3.901	1%	3.841	-1%
MAY	3.568	3.369	-6%	3.580	0%	3.907	3.871	-1%	3.820	-2%
JUNE	4.147	3.884	-6%	4.184	1%	4.327	4.314	0%	4.335	0%
JULY	4.380	4.126	-6%	4.483	2%	4.785	4.695	-2%	4.848	1%
AUGUST	3.216	3.236	1%	3.604	12%	3.806	3.976	4%	4.187	10%
SEPTEMBER	2.308	2.583	12%	2.800	21%	2.934	3.315	13%	3.381	15%
OCTOBER	1.749	1.696	-3%	1.828	5%	2.592	2.456	-5%	2.514	-3%
NOVEMBER	963	995	3%	1.110	15%	1.681	1.723	3%	1.806	7%
DECEMBER	688	913	33%	907	32%	1.228	1.538	25%	1.474	20%
TOTAL	28.176	28.090	0%	30.253	7%	34.577	35.623	3%	35.829	4%

2017	GROUP 1 (59°)					GROUP 2 (239°)				
	SPP	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]	%	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]
JANUARY	650	663	2%	833	28%	1.000	1.061	6%	1.182	18%
FEBRUARY	1.027	1.129	10%	1.185	15%	1.481	1.778	20%	1.560	5%
MARCH	1.883	1.980	5%	2.060	9%	2.508	2.533	1%	2.535	1%
APRIL	3.004	3.208	7%	2.992	0%	3.513	3.960	13%	3.325	-5%
MAY	3.357	3.453	3%	3.455	3%	3.681	3.975	8%	3.726	1%
JUNE	3.786	3.832	1%	3.861	2%	4.042	4.326	7%	4.027	0%
JULY	4.086	4.049	-1%	4.272	5%	4.419	4.686	6%	4.546	3%
AUGUST	3.213	2.950	-8%	3.596	12%	3.791	3.694	-3%	4.123	9%
SEPTEMBER	2.564	2.510	-2%	2.850	11%	3.291	3.245	-1%	3.383	3%
OCTOBER	1.750	1.731	-1%	2.007	15%	2.575	2.483	-4%	2.694	5%
NOVEMBER	976	1.157	19%	1.190	22%	1.605	1.866	16%	1.834	14%
DECEMBER	656	856	30%	802	22%	1.056	1.435	36%	1.163	10%
TOTAL	26.954	27.517	2%	29.104	8%	32.962	35.042	6%	34.099	3%

2018	GROUP 1 (59°)					GROUP 2 (239°)				
	SPP	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]	%	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]
JANUARY	790	663	-16%	958	21%	1.306	1.061	-19%	1.471	13%
FEBRUARY	867	1.129	30%	981	13%	1.103	1.778	61%	1.160	5%
MARCH	1.890	1.980	5%	2.067	9%	2.509	2.533	1%	2.609	4%
APRIL	2.920	3.208	10%	3.269	12%	3.525	3.960	12%	3.821	8%
MAY	2.965	3.453	16%	3.286	11%	3.276	3.975	21%	3.549	8%
JUNE	3.647	3.832	5%	3.923	8%	3.708	4.326	17%	3.919	6%
JULY	3.743	4.049	8%	4.149	11%	4.024	4.686	16%	4.398	9%
AUGUST	3.390	2.950	-13%	3.846	13%	3.959	3.694	-7%	4.323	9%
SEPTEMBER	2.365	2.510	6%	2.685	14%	3.001	3.245	8%	3.200	7%
OCTOBER	1.548	1.731	12%	1.876	21%	2.261	2.483	10%	2.519	11%
NOVEMBER	759	1.157	52%	981	29%	1.281	1.866	46%	1.560	22%
DECEMBER	547	856	57%	754	38%	878	1.435	63%	1.152	31%
TOTAL	25.432	27.517	8%	28.777	13%	30.830	35.042	14%	33.681	9%

2019	GROUP 1 (59°)					GROUP 2 (239°)				
	SPP	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]	%	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]
JANUARY	611	663	8%	776	27%	840	1.061	26%	968	15%
FEBRUARY	992	1.129	14%	1.195	20%	1.563	1.778	14%	1.752	12%
MARCH	2.337	1.980	-15%	2.690	15%	3.108	2.533	-19%	3.341	7%
APRIL	2.554	3.208	26%	2.878	13%	2.983	3.960	33%	3.258	9%
MAY	3.465	3.453	0%	3.735	8%	3.621	3.975	10%	3.868	7%
JUNE	3.827	3.832	0%	4.123	8%	3.941	4.326	10%	4.311	9%
JULY	3.935	4.049	3%	4.275	9%	4.129	4.686	13%	4.504	9%
AUGUST	3.475	2.950	-15%	3.879	12%	4.001	3.694	-8%	4.367	9%
SEPTEMBER	2.424	2.510	4%	2.911	20%	3.182	3.245	2%	3.454	9%
OCTOBER	1.386	1.731	25%	1.722	24%	2.163	2.483	15%	2.552	18%
NOVEMBER	852	1.157	36%	1.075	26%	1.411	1.866	32%	1.663	18%
DECEMBER	556	856	54%	786	41%	940	1.435	53%	1.227	31%
TOTAL	26.415	27.517	4%	30.046	14%	31.882	35.042	10%	35.265	11%

2020	GROUP 1 (59°)					GROUP 2 (239°)				
	SPP	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]	%	REAL SPP [kWh]	MODEL [kWh]	%	PVGIS [kWh]
JANUARY	683	663	-3%	950	39%	1.208	1.061	-12%	1.558	29%
FEBRUARY	1.128	1.129	0%	1.428	27%	1.695	1.778	5%	1.917	13%
MARCH	1.794	1.980	10%	2.087	16%	2.304	2.533	10%	2.541	10%
APRIL	2.640	3.208	22%	3.038	15%	3.123	3.960	27%	3.448	10%
MAY	3.245	3.453	6%	3.687	14%	3.565	3.975	12%	3.980	12%
JUNE	3.337	3.832	15%	3.898	17%	3.316	4.326	30%	3.932	19%
JULY	3.856	4.049	5%	4.425	15%	4.099	4.686	14%	4.721	15%
AUGUST	3.055	2.950	-3%	3.854	26%	3.634	3.694	2%	4.336	19%
SEPTEMBER	1.930	2.510	30%	2.737	42%	2.664	3.245	22%	3.286	23%
OCTOBER	1.440	1.731	20%	1.874	30%	2.184	2.483	14%	2.489	14%
NOVEMBER	902	1.157	28%	1.186	32%	1.680	1.866	11%	2.012	20%
DECEMBER	540	856	58%	791	46%	861	1.435	67%	1.239	44%
TOTAL	24.551	27.517	12%	29.955	22%	30.333	35.042	16%	35.458	17%

Average energy production of the SPP in 2016, 2017, 2018, 2019, 2020 are compared with the designed program and PVGIS program results as shown in Table 3. In the calculations, PVGIS-SARAH 2 meteorology data in 2016, 2017, 2018, 2019, 2020 are used for the designed program and PVGIS program. The designed program calculates the total energy production of both groups for 2016-2020 years with a 1,5% difference. The PVGIS program calculates the total energy production of both groups with a 5,3% difference. As a result of the comparison, the designed program gave more realistic results than the PVGIS program when using the same meteorology data.

The results calculated by the designed program are closer to real SPP energy production than the PVGIS program. When the calculation results are compared with groups at different directions, this program gives more correct results for angular differences. Each program calculation result is compared with using SARAH 2 meteorology data. In this way, the designed program results can be compared with the PVGIS program results at the same conditions, as shown in Table 4.

Table 4. General comparison table

INDEX	INFORMATION	GROUP1 (59°) (kWh)	GROUP2 (239°) (kWh)	TOTAL (kWh)	RATE (%)
A	PROJECT ENERGY CALC.	32.596	36.618	69.214	18%
	2016 PRODUCTION	28.176	34.577	62.752	-
	2016 MODEL RESULT	28.090	35.623	63.713	2%
	2016 PVGIS RESULT	30.253	35.829	66.082	5%
	2017 PRODUCTION	26.954	32.962	59.916	-
	2017 MODEL RESULT	27.031	34.229	61.260	2%
	2017 PVGIS RESULT	29.104	34.099	63.203	5%
	2018 PRODUCTION	25.432	30.830	56.262	-
B	2018 MODEL RESULT	26.266	33.585	59.851	6%
	2018 PVGIS RESULT	28.777	33.681	62.458	11%
	2019 PRODUCTION	26.415	31.882	58.297	-
	2019 MODEL RESULT	27.724	35.212	62.936	8%
	2019 PVGIS RESULT	30.046	35.265	65.311	12%
	2020 PRODUCTION	24.551	30.333	54.884	-
	2020 MODEL RESULT	27.792	35.416	63.208	15%
	2020 PVGIS RESULT	29.954	35.458	65.412	19%
	2016-2020 PRODUCTION	131.527	160.585	292.112	-
C	2016-2020 MODEL RESULT	136.903	174.065	310.968	6%
	2016-2020 PVGIS RESULT	148.134	174.332	322.466	10%
	2016-2020 REEL PRODUCTION AVERAGE	26.305	32.117	58.422	-
D	2016-2020 MODEL PRODUCTION AVERAGE	27.381	34.813	62.194	6%
	2016-2020 PVGIS PRODUCTION AVERAGE	29.627	34.866	64.493	10%

As indicated in row A of Table 4, the SPP project plan is the predicted energy production 32596 kWh for Group 1, 36618 kWh for Group 2 and 69214 kWh in total. When the five-year average energy production of the system is compared with the project plan, it was seen that 18% more energy production is expected in the project.

In the B row of Table 4, yearly SPP energy productions are compared with the energy production estimations of the designed program and PVGIS program results. PVGIS SARAH 2 meteorological data of 2016, 2017, 2018, 2019, 2020 years are used in the designed program. The results obtained are compared with real SPP energy production and it has been observed that maximum annual deviation is 15%. The maximum annual deviation for the result of the PVGIS calculation is 19%.

In the C row of Table 4, the designed program, PVGIS program and real SPP total energy productions are compared with data of 2016, 2017, 2018, 2019, 2020 years. The SPP produced 292112 kWh of energy in five years. The program calculated the energy production as 310968 kWh. As a result, it has been shown that there is a 6 % deviation the in the program results in total of five years. On the other hands, PVGIS program calculated total energy production 322466 an % 10 upper from the real system generation.

In the D row of Table 4, the annual average energy productions of real SPP, designed model and PVGIS are compared for the years between 2016 and 2020. The average results of designed model are compared with real SPP energy production and it has been observed that maximum annual average deviation is 6%. The maximum annual average deviation for the result of the PVGIS calculation is 10%. The comparison graph of produced and estimated energy is shown in Figure 15.

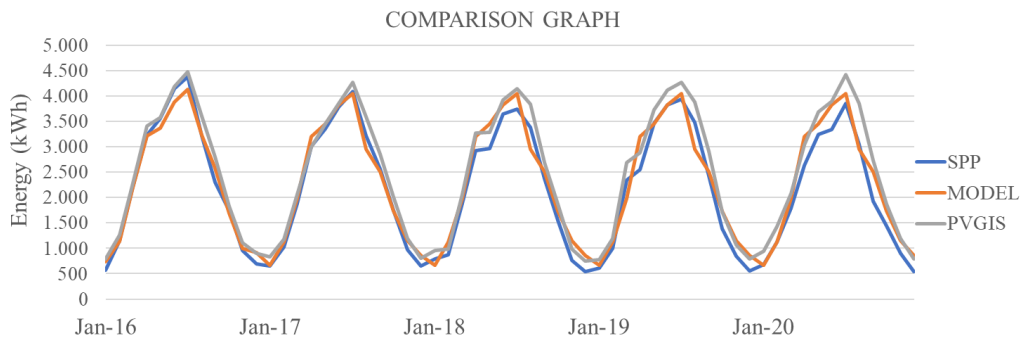


Figure 15. Comparison of the programs results

Program input parameters of the calculation programs are similar but there are some differences in the result parameters. The main inputs in the programs include system panel maximum power, coordinate information, meteorology data, mounting direction and angle, panel type and loss rate. Additionally, the designed program uses system characteristic parameters in the datasheet. As a result of the calculation, the system's monthly and annual total energy production forecast can be obtained by using this program. Table 5 shows the output parameters produced by the programs. As seen in table, the designed program output gives more parameters of the panel and system than the others.

Table 5. Result parameter comparison table

PARAMETER	PVGIS	PROGRAM
Beam Irradiance (W/m ²)	x	x
Diffuse Irradiance (W/m ²)	x	x
Reflected Irradiance (W/m ²)	x	x
Ambient Temperature (C)	x	x
Wind Speed (m/s)	x	x
Plane of Array Irradiance (W/m ²)		x
Cell Temperature (C)		x
DC Array Output (W)		x
AC System Output (W)	x	x

Solar Altitude Angle (°)	x	x
Declination Angle (°)		x
Azimuth Angle (°)		x
Hour Angle		x
AOI Angle of Incidence (°)		x
Day Length (hour)		x
LST Local Solar Time (hour)		x
PV Maximum Power (W)		x
PV Open Circuit Voltage (V)		x
PV Short Circuit Current (A)		x

5. Conclusion

In this study, a model and program are designed for more realistic SPP energy production calculations. This program is used to calculate the amount of energy production to be produced by using the position and mounting angles of PV, the characteristic values of the PV panels and inverters parameters in the datasheets.

The calculation results of designed program are desired to be closest to the real energy production and to minimize the errors. In addition to, more realistic results tried to be obtained on different operating conditions. In the monthly comparisons, closer results to SPP energy production is obtained by means of designed program than the other program.

When the energy production of the SPP is examined, Group 2 produces 22% more energy than Group 1. According to the results of the designed program, it estimates 27% more energy production. On the other hand PVGIS calculated 17% difference. The results are close to each other.

The designed program calculates 15% more energy production yearly if the panel groups are directed the south with 30° tilt angle. These results show remarkable effect of panel setup on energy production.

There are 2-15% differences between the designed program calculation results and the real SPP energy production. PVGIS-SARAH 2 meteorology data are used in this program. As a result of the calculations, more sensitive and realistic results for this program are obtained than other program.

Unlike other programs that use average value and proportional approaches in calculations, the designed program uses panel and inverter catalog values. In this way, it provides the opportunity to make calculations for the existing products or prototype by entering the datasheet values manually. There are many products with the same power value on the market, but their quality and technology, efficiency and characteristic curves are different from each other. The designed program provides the opportunity to make realistic calculations for different products.

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