Celal Bayar University Journal of Science

Determination of Optimal DC/AC Ratio for Grid-Connected Photovoltaic Systems

Mehmet Fatih Beyoğlu[1]*, Metin Demirtaş[1]

[1] Department of Electrical and Electronics Engineering, Balıkesir University, Balıkesir, Türkiye
* fatih.beyoglu@baun.edu.tr
* Orcid No: 0000-0001-8092-7014

Received: 08 November 2022
Accepted: 02 March 2023
DOI: 10.18466/cbayarfbe.1200284

Abstract

Suitability evaluation of a location for solar power generation plant installation requires long-term measurements and calculations. The correct calculation of the project power and energy production values of the solar power plant (SPP) is very important as it directly affects the payback period of the project cost. The effect of the DC/AC ratio used in an inverter selection is a crucial parameter in determining the sizing of SPP. In this study, a model was used to find the closest estimation values. Irradiance values coming to SPP in Balıkesir/Turkey were simulated and DC energy at the inverter input was calculated. The results obtained from the calculation were compared with actual production values. To determine the optimum DC/AC ratio of the existing installed SPP system, calculations were made with two different methods. Estimation of energy production values is calculated for different angles and different DC/AC ratios of inverters. It is vital that the SPP consists of two groups with different directions and the same capacities in terms of comparing the accuracy of the calculation. Energy production calculations, including the hourly meteorological data and catalog values of the system in the developed model, are desired to provide the closest prediction values for energy production of the real system. The optimum DC/AC ratio also varies depending on the coordinates, direction and angle of the PV system. As a result, it has been observed that the direction and location of the PV system affect the selection of inverter power. Thus, it is important to calculate this ratio for efficient working conditions of each system. Optimal values of ratios and efficiencies for Groups 1 and 2 are calculated as 1.28, 1.35, 91.55% and 90.62%, respectively.

Keywords: Clipping, DC/AC ratio, Grid, Performance analysis, Sizing ratio, Solar energy

1. Introduction

Solar energy, one of the most important renewable energy generation sources, is a safe, clean, free, non-polluting and endless energy source. The efficiency of PV systems depends on several climatic factors, such as solar irradiance, ambient temperature and the state of solar panels such as their age and soiling.

For the specified coordinates, the irradiance coming to the surface can be calculated by considering the motion of the earth around the sun and sun angle during the day, the slope and direction angle mounted solar panel system. Karafil et al. [1] examined the effects of panel inclination angle on energy production in Bilecik province. Rustemli et al. [2] compared the solar energy system with a solar tracking system and fixed mounting. Beyoglu [3] compared energy productions of fixed and 2-axis tracking photovoltaic solar energy systems in Balikesir province. Beyoglu et al. [4] compared different energy production estimation programs with the actual energy production data of the solar power plant (SPP) established in Balikesir province. Aboot [5] studied calculating sun angles for any time and location using MATLAB code. After that he analyzed the pattern of solar angles and the solar path. Jazayeri et al. [6] studied a simulation model to calculate the sun's position and the incidence angle of sunlight beams on the surface of PV modules with mounted any slope angle and location on the Earth. Demoulias [7] developed a new and simple analytical method to calculate the optimum inverter size for grid-connected PV plants anywhere. Wang et al. [8] introduced the optimum sizing ratio of photovoltaic (PV) array capacity and compared it to the nominal inverter input capacity. The optimum ratio was determined by empirical and analytical approaches. Faranda et al. [9] presented an analytical formulation for annual DC power production by analyzing available solar irradiance data for some selected locations. A general efficiency characteristic curve fitted for different solar inverter types, using approximated function. A new analytical method is proposed to estimate the optimal size of PV plants from energy production. Pandey et al. [10] presented a new method to calculate inverter power clipping loss because of an oversized PV array, in other words, a high DC/AC ratio. Camps et al. [11] studied a new approach to the experimental validation of the optimal PV to inverter sizing ratio value for the energy yield maximization of an on-grid PV system. They used a custom workbench to simulate a solar array for different technical configurations and environmental data. Azzolini et al. [12] evaluated the expected curtailment associated with Volt-VAr control. Yearlong quasi-static time-series (QSTS) simulations were conducted on a realistic distribution feeder under various PV system design considerations. Overall, this paper found that the amount of curtailed energy is low (<0.55%) when compared to the total PV energy production in a year. Notton et al. [13] studied an optimal sizing methodology based on an energy approach. This method applied on-grid photovoltaic systems and used PV module technology and slope, the inverter type and the location information. Ferna´ndez et al. [14] proposed the use of a fuzzy system evaluating a feature space extracted from the daily power production profile of a photovoltaic solar plant. The fuzzy system proposed is able to detect inverter power-limiting situations, as well as stages where the photovoltaic solar plant is showing steady-state power production. Deschamps et al. [15] studied to perform and analyze the optimum inverter sizing for large-scale on-grid solar photovoltaic. The solar irradiance distribution is analyzed and its potential effects on inverter sizing were performed. Balfour et al. [16] described how performance problems could be ``masked" or not readily evident by several causes, PV system configuration, instrumentation design, installation, maintenance, contract clauses, identified management and operational practices. A simple method based on a duration curve is introduced to overcome shortcomings of performance ratio based on nameplate capacity and performance index based on hourly simulation when quantifying masking effects. Inverter clipping and pyranometer soiling were presented as two examples of the new method. Zidane et al. [17] aimed to select the optimum inverter size for large-scale on-grid PV power plants based on the several possible combinations of PV array and inverter. Choi [18] studied the effect of installation location on PV inverter lifetime and DC/AC ratio. Khatib et al. [19] studied a simple iterative method to optimize the inverter size for an on-grid photovoltaic system. The developing models are used hourly solar irradiance and ambient temperature data of the PV systems. Moreover, an optimized inverter and a conventionally sized inverter are compared in this study. In another study, Khatib et al. [20] used the iterative method for optimizing inverter size on five solar power plants in Malaysia. DC/AC ratio was optimized at different load levels using different commercial inverters models.

In this study, the effects of the DC/AC ratio, which is irradiance a determining parameter in the inverter selection, in the sizing of an SPP were investigated. The incoming irradiance values of a power plant in Balikesir/Turkey were used to calculate DC energy at the inverter input. The calculation results were compared with the real production values and compatible. The energy productions of PV plants installed at different angles and different inverter powers have been compared. To determine the optimum DC/AC ratio of the existing installed SPP system, calculations were made with two different methods to compare the simulation results.

In this program, the energy production calculations were made using real meteorology data, considering the location of the system, the mounting angle and catalog values. Turkish State Meteorological Service (TSMS) data were used as meteorological data. It was observed that the program gave realistic results.

Nomenclature

η_{norm}	*Inverter maximum efficient*
η_{ref}	*Reference efficient*
η	*Inverter actual efficient*
ξ	*DC power ratio*
V_{PV}	*Output voltage of PV*
V_{oc}	*Open circuit voltage*
I_{sc}	*Short circuit current*
P_{max}	*Maximum power of PV*
t	*Time*
P_{DC}	*PV actual input power*
P_{DC0}	*Inverter maximum input power*
P_{AC0}	*Inverter maximum output power*
P_{irated}	*Inverter nominal power*
$P_{PV(rated)}$	*Total PV nominal power*
$P_{mpp.stc}$	*PV instant DC power*
R_s	*Sizing ratio, DC/AC ratio*
N_s	*Serial PV number*
N_p	*Parallel PV number*

2. Energy Production Estimation Program

An analytical energy generation estimation program that is designed on MATLAB/Simulink was used for the calculations. This program consists of the solar position calculation, surface irradiance calculation, PV system and inverter efficiency calculation modules. A block diagram of the PV system model is given in Figure 1. The designed program needs hourly meteorology data, geographic coordinates with montage info of SPP and some system information for calculation. Output of the

Celal Bayar University Journal of Science
Volume 19, Issue 1, 2023, p 19-29
Doi: 10.18466/cbayarfbe.1200284

program gives the panel and inverter output energy production values hourly. The program is used to calculate the inverter DC input and AC output power generation data. Since this program uses panel and inverter datasheets, it gives more accurate and detailed results in this calculations.

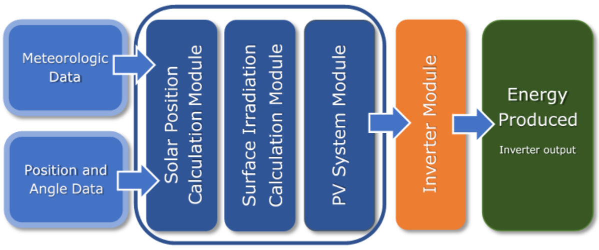

Figure 1. Block diagram of designed program modules

Inverter efficiencies are given as constant values in the datasheet, but in fact, the efficiency decreases rapidly at low power values. Therefore, the inverter efficiency module was used to estimate more realistic results at low power values. The Simulink diagram of the PV system model is given in Figure 2. This diagram consists of three main blocks which are solar position calculation, surface irradiance calculation, PV system and inverter efficiency calculation modules.

2.1. 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 high efficiency. The system follows the maximum power point under all conditions. The fixed losses of the system are also important during low irradiance and the system's efficiency decreases rapidly. Figure 3 shows the efficiency curve of the inverter used in the system. The efficiency curve is calculated by the module shown in Figure 4. The efficiency equation of the inverter can be written as follows:

$$\eta = \frac{\eta_{norm}}{\eta_{ref}}\left(-0.016138\,\xi - \frac{0.0059}{\xi} + 0.9858\right) \qquad \textbf{(1)}$$

where,

$$\xi = \frac{P_{DC}}{P_{DC0}} \text{ and } P_{DC0} = \frac{P_{AC0}}{\eta_{norm}}$$

Inverter efficiency is calculated by considering the input power at the optimum operating conditions and instantaneous input power. It is given Equation (1) [21]. Where η, η_{norm}, η_{ref}, P_{DC}, P_{DC0} and P_{AC0} are the instant efficiency, the nominal efficiency, the reference efficiency, the instant input power, the maximum input power and the maximum AC output power of the inverter, respectively.

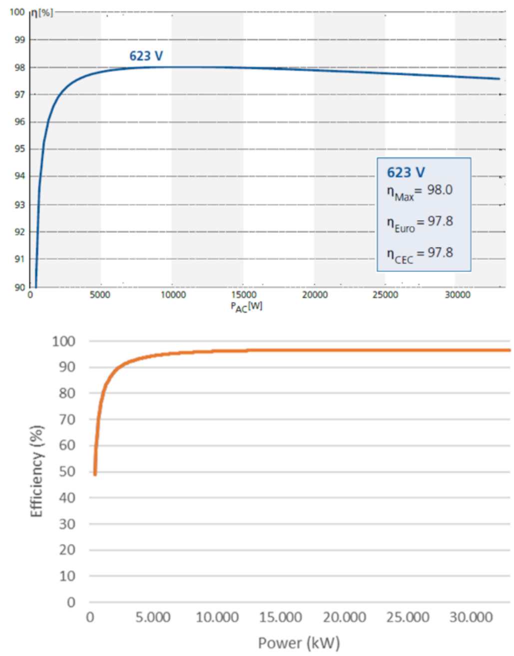

Figure 3. The inverter efficiency curves in catalog and module output

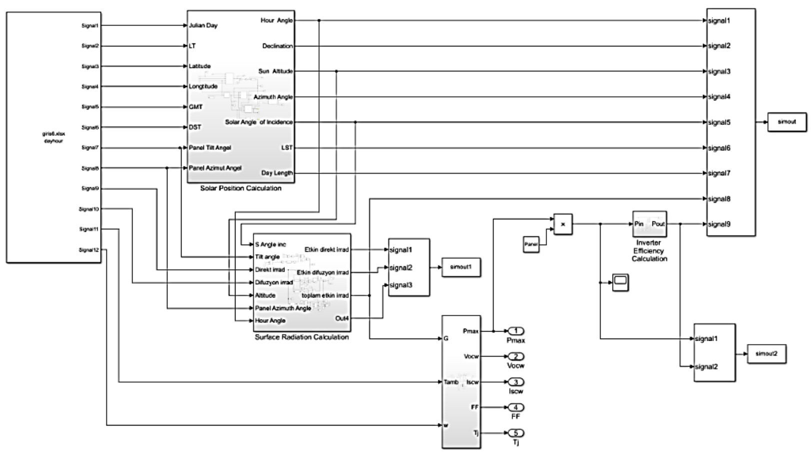

Figure 2. The Simulink diagram of designed program modules

Celal Bayar University Journal of Science
Volume 19, Issue 1, 2023, p 19-29
Doi: 10.18466/cbayarfbe.1200284

The module that calculates the inverter efficiency and output power to determine input power is shown in Figure 4.

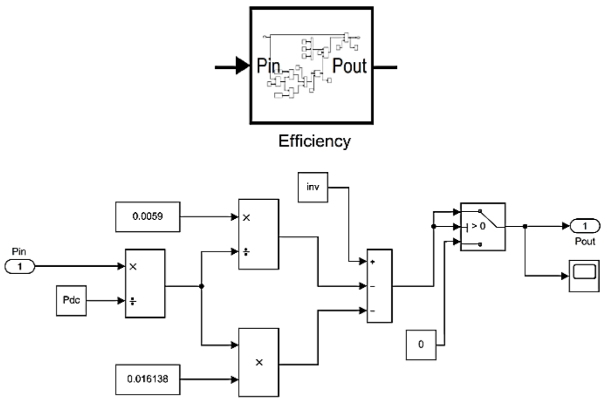

Figure 4. The module calculating inverter efficiency

2.2. DC/AC Ratio Module

The DC/AC or sizing ratio (R_s) is the ratio of the PV array nominal power ($P_{PV(rated)}$) to the nominal power of the inverter (P_{irated}) power at the standard test conditions. This ratio is used to express the optimum combination between the PV array and inverter. The sizing ratio is given in Equation (2) [17,19].

$$R_s = \frac{P_{PV\ (rated)}}{P_{i(rated)}} \quad \textbf{(2)}$$

The PV array nominal power ($P_{PV(rated)}$) can be determined using Equation (3).

$$P_{PV(rated)} = P_{mpp,stc} \,.\, N_s .\, N_p \quad \textbf{(3)}$$

Where $P_{mpp,stc}$, N_s and N_p are the PV module nominal maximum power at standard test conditions, the number of PV modules connected in series and parallel, respectively.

If the R_s value is in interval $0 < R_s < 1$ then the inverter is oversized. For $R_s > 1$, the inverter is undersized, and leads to a clipping effect due to power limitation when the daily power generation of the system exceeds the inverter power [8].

3. Program Data

The energy production of a SPP consisting of two independent groups, established in Balikesir (39.6N 27.9E), was examined. The each group has 108 polycrystalline panels with 250 W and an inverter output power 27500 VA. As shown in Figure 5, it is directed at 59° (Group 1) and 239° (Group 2) symmetrical angles and mounted on 17° angled roof. Circuit diagram of on-grid SPP system with two inverters is given in Figure 6. The inverter has 3 MPPT inputs, and PV arrays consisting of 18 serial modules in 2 parallel strings are connected to each input. PV array voltage-current graph is given in Figure 7.

Table 1. 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	AC Rated Output	27500 VA
Pmax	250 W		
Efficiency	15.37%		
		DC/AC Ratio	≈1
PV DC Total Power	27000 W		

Table 2. General comparison table.

INFORMATION	GROUP1 (59°) (kWh)	GROUP2 (239°) (kWh)	TOTAL (kWh)	FAULT RATE (%)
2020 REAL PRODUCTION	24550	30333	54883	-2.4%
2020 MODEL RESULT	23922	29649	53571	

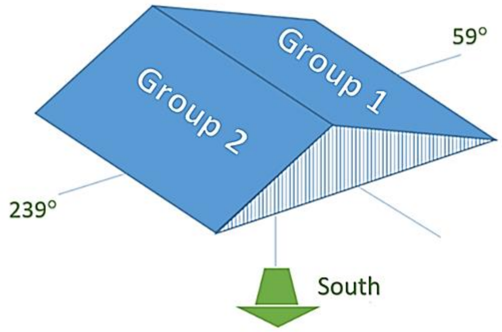

Figure 5. Roof view of the real system.

The real SPP system catalog information is given in Table 1.

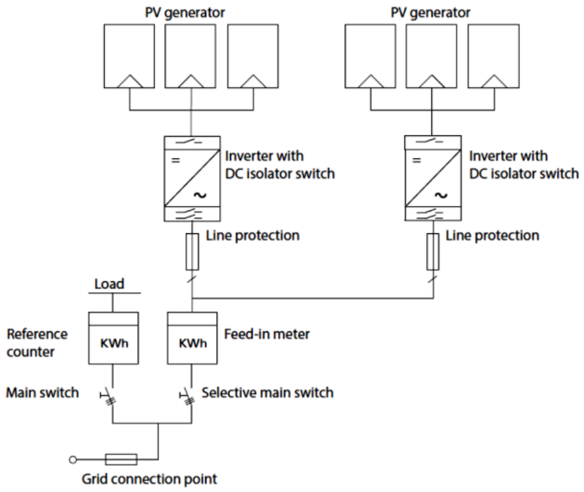

Figure 6. Circuit diagram of a system with two inverters.

When Table 1 is examined, it is seen that the DC power of the real system is 27000 W and the inverter output power is 27500 VA. As a result, the DC/AC ratio is approximately 1. This value is obtained from the catalog information of the real system.

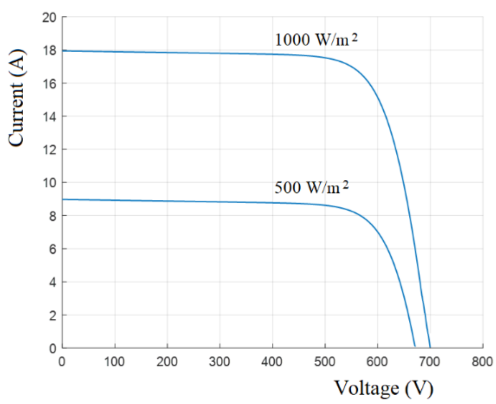

Figure 7. The effect of series/parallel connection of PV arrays on the current-voltage curve.

3.1 Program Calculation

The real SPP annual energy production values were compared with the results of the developed program for Group1 and Group 2. The comparison results are given in Table 2.

The SPP produced 54883 kWh in 2020. The program calculated that the system would produce 53571 kWh by using meteorological data of 2020. In the comparison table, a deviation of 2.4% was observed with the calculation results. The results are stable and realistic at different angle values for both PV groups. DC/AC ratio comparison tables are presented for Group 1 and Group 2 in Table 3 and Table 4, respectively.

Table 3. DC/AC ratio comparison table for Group 1

GROUP 1					
DC/AC RATIO	POWER (W)	INPUT (kWh)	OUTPUT (kWh)	CLIPPING (kWh)	RATIO (%)
0.8	33750	23843	23843	0	0.0%
0.9	30000	23893	23893	0	0.0%
1.0	27000	23929	23926	4	0.0%
1.1	24500	23956	23916	40	0.2%
1.2	22500	23975	23844	131	0.5%
1.3	20750	23988	23714	274	1.1%
1.4	19300	23997	23521	476	2.0%
1.5	18000	24002	23266	736	3.1%

Table 4. DC/AC ratio comparison table for Group 2

GROUP 2					
DC/AC RATIO	POWER (W)	INPUT (kWh)	OUTPUT (kWh)	CLIPPING (kWh)	RATIO (%)
0.8	33750	29544	29544	0	0.0%
0.9	30000	29609	29605	4	0.0%
1.0	27000	29658	29558	100	0.3%
1.1	24500	29693	29369	324	1.1%
1.2	22500	29718	29123	595	2.0%
1.3	20750	29736	28810	926	3.1%
1.4	19300	29748	28483	1265	4.3%
1.5	18000	29755	28152	1603	5.4%

Comparisons of Group 1 and Group 2 for annual energy production at different DC/AC ratios are given in Table 3 and Table 4. For DC/AC=1, it is calculated that Group1 will produce 23926 kWh and Group 2 will produce 29558 kWh. For DC/AC=1.5, it is calculated that Group1 will produce 23266 kWh and Group 2 will produce 28152 kWh. For DC/AC =1.5, it is predicted that Group 1 will produce 3.1% and Group 2 will produce 5.4% energy less than DC/AC=1. Although the system power decreases at DC/AC= 1.5, it is remarkable that the energy production higher than DC/AC=1 due to the more efficient operation of inverter at low power. As shown in Figure 8, the direction of installed system affects the energy production amount. While sizing the system, it should be considered that the transformer power, cross section of cable and connector elements will decrease. As a result, whole system installation cost will decrease with the selection of suitable inverter power.

Celal Bayar University Journal of Science
Volume 19, Issue 1, 2023, p 19-29
Doi: 10.18466/cbayarfbe.1200284

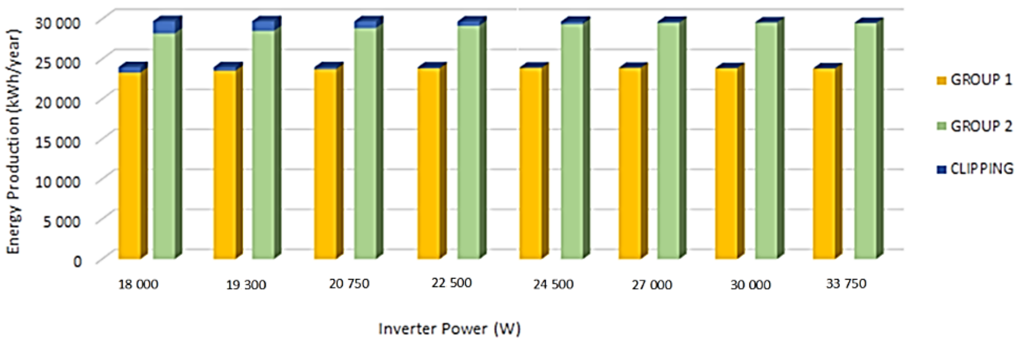

Figure 8. Energy productions of inverter groups.

The energy productions of Groups 1 and 2 for 2020 are shown in Figure 9 in watts/hour. The produced energy data are arranged from the higher values to the lower values so that they can be seen more clearly on the graph. The lines where the production will be clipping for different DC/AC ratios are marked on the Figure 9. As shown from the graph, the clipping sections are at the maximum power production area. This area is a small part of the annual energy production amount. The amount of clipping energy can be seen more clearly on the Figure 9.

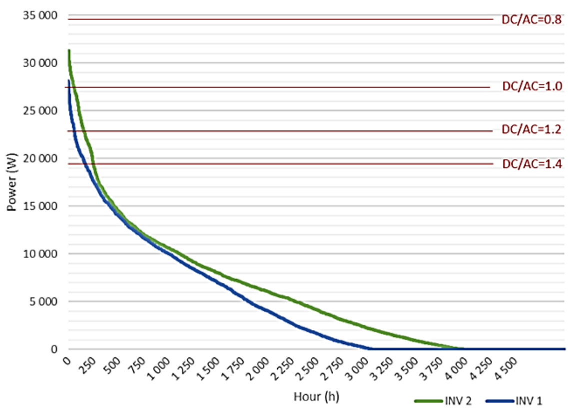

Figure 9. The power production and clipping of inverter groups.

The energy production curve modeled according to the highest power generation day of 2020 for the different inverter powers of SPP is given on the Figure 10.

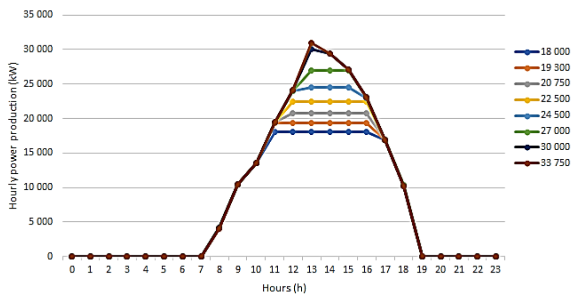

Figure 10. The maximum energy production and clipping values of inverter.

The produced energy according to DC/AC ratio is given Table 5 for the same day and different hours.

Table 5. Energy production according to DC/AC ratio.

DC/AC RATIO	INVERTER POWER (W)	PRODUCED ENERGY (Wh/year)
1.5	18000	163453
1.4	19300	171257
1.3	20750	178679
1.2	22500	187432
1.1	24500	195448
1	27000	202953
0.9	30000	208344
0.8	33750	209246

As seen from the Figure 10 and Table 5, the inverter clipping value (209246-163453=45793 W) is over the rated inverter power 18000W. There is a 22% energy production difference between the highest power and the lowest power. But SPP does not produce the maximum power during the whole year. As a result, the annual energy difference produced by the system is around 5%.

The SPP has two PV system groups with the same power and symmetrically placed. When the energy productions of two groups are analyzed, there is a 19% difference in between them.

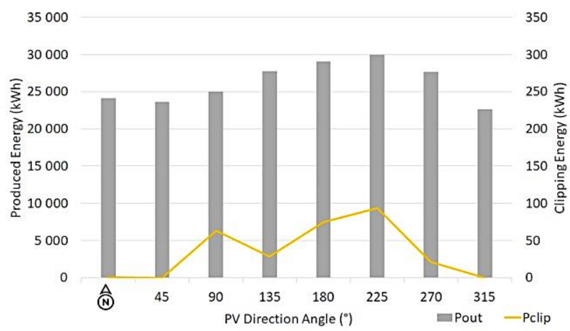

Figure 11. The effect of direction on energy production and clipping.

Celal Bayar University Journal of Science
Volume 19, Issue 1, 2023, p 19-29
Doi: 10.18466/cbayarfbe.1200284

Calculations were made for different directions to examine the effect of direction of the system on energy production. According to the designed program, if the same panel groups and inverter of real SPP are assembled in the different directions and at same tilt angle, the amount of energy they would generate would be as given in Table 6 and Figure 11.

Table 6. Annual energy production comparisons for different direction angels (DC/AC Ratio = 1).

DIRECTION ANGLE (º)	PV PRODUCED ENERGY *Epv (kWh)*	INVERTER OUTPUT ENERGY *Einv (kWh)*	CLIPPING ENERGY *Eclip (kWh)*
0	29407	24159	1
45	28690	23604	0
90	30429	24995	64
135	33667	27713	29
180	35397	29070	75
225	36513	29950	93
270	33740	27692	21
315	27650	22642	0

The PV system energy productions are calculated for DC/AC=1 as given in Table 6 by using different directions and meteorological data for 2020. Program calculates that PV would produce the minimum of 20202 kWh at 335° and the maximum of 30000 kWh at 215° when the system direction is changed. There is a 32% difference between the minimum and maximum energy production.

It is estimated that the highest average annual energy production of existing system will be 30000 kWh in a year if the system operates at 215 degrees by using meteorology data for 2020. This result indicated that the panel's direction was important in selecting inverter power.

4. Calculation of Optimum Sizing Ratio

There are different methodologies to determine the optimal power of an inverter. Of these, DC/AC ratio was calculated with the energy produced in the PV panel and operation method with maximum inverter efficiency. Information about the method and the results obtained are described in detail in the subsections.

4.1. Iterative Conversion Efficiency Method

On-grid inverters are usually sized according to the rated power of the PV array. Inverters usually follow the maximum power point to produce maximum power. However, since solar irradiance varies according to location and meteorological data, the output power of PV panels is also variable. At low solar irradiance levels, the PV array generates less than its rated power. Therefore, the inverter is operated at lower efficiency. Consequently, it is vital to find the optimal size of inverter for effective energy production using a PV system [19]. An example graph showing the variation of DC/AC ratio with inverter efficiency is presented in Figure 12.

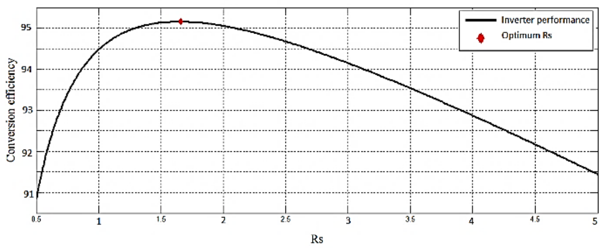

Figure 12. Optimization of the inverter sizing ratio.

Figure 13 shows the proposed optimization algorithm for inverter size in a grid-connected PV system. In the beginning, the PV system parameters such as the rated power of the PV array, the temperature coefficient, location and direction of the PV module are determined. With these parameters, hourly solar irradiance and ambient temperature records are used to obtain the inverter input DC power. Then, DC input power values are used to calculate inverter efficiency with the iteration. Loop of R_s was set in the range of 0.5 to 5.

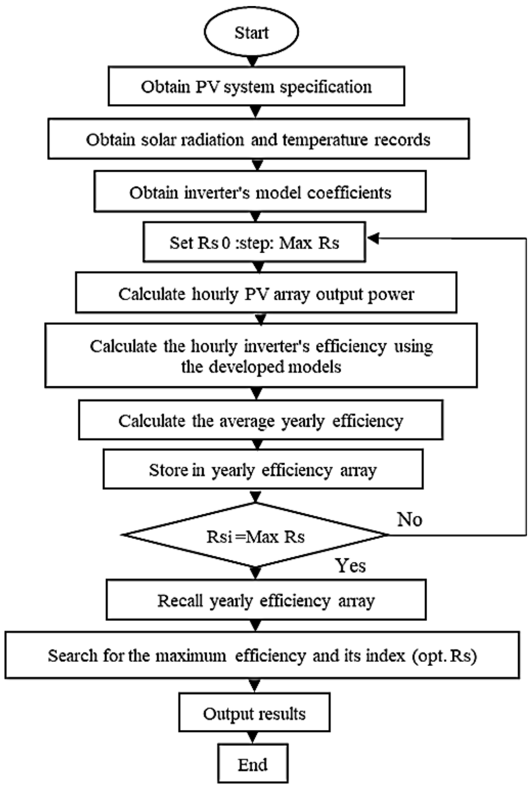

Figure 13. Flowchart for the inverter's optimal efficiency

The PV array output is calculated hourly using the complicated PV model described in Equation (1). After that, the annual average efficiency is calculated. The loop is being repeated until R_s reaches its maximum value. Finally, when R_s reaches its maximum value, optimum R_s for the maximum efficiency is found.

In Table 7, the conversion efficiency and energy production values are obtained by changing the DC/AC ratio between 0.5 and 5 by using 0.5 steps for Group 1. Change of values was graphed Figure 14(a). For Group 1, the optimum inverter power was calculated as 21094 W and DC/AC ratio is equal to 1.28. For this value, it is predicted that the inverter will operate with an average efficiency of 91.55% and produce 23747 kWh of energy per year.

Table 7. Comparison table of conversion efficiency for Group 1.

GROUP -1

DC/AC RATIO	INVERTER POWER (W)	CONVERSION EFFICIENCY (%)	PRODUCED ENERGY (kWh)
0.5	54000	87.58%	23531
1.0	27000	91.04%	23926
1.5	18000	91.15%	23266
2.0	13500	89.04%	21628
2.5	10800	85.82%	19743
3.0	9000	82.11%	17901
3.5	7714	78.31%	16264
4.0	6750	74.80%	14847
4.5	6000	71.73%	13633
5.0	5400	68.83%	12601
OPTIMUM DC/AC RATIO FROM CONVERSION EFFICIENCY			
1.28	21094	91.55%	23747

Table 8. Comparison table of conversion efficiency for Group 2.

GROUP -2

DC/AC RATIO	INVERTER POWER (W)	CONVERSION EFFICIENCY (%)	PRODUCED ENERGY (kWh)
0.5	54000	87.35%	29139
1.0	27000	90.32%	29558
1.5	18000	90.49%	28152
2.0	13500	89.28%	26332
2.5	10800	86.84%	24310
3.0	9000	83.90%	22278
3.5	7714	80.82%	20444
4.0	6750	77.72%	18813
4.5	6000	74.72%	17369
5.0	5400	71.95%	16102
OPTIMUM DC/AC RATIO FROM CONVERSION EFFICIENCY			
1.35	20000	90.62%	28645

In Table 8, the conversion efficiency and energy production values obtained by changing the DC/AC ratio between 0.5 and 5 with 0.5 steps are presented for Group 2. Change in values was graphed in Figure 14(b). For Group 2, the optimum inverter power was calculated as 20000 W and DC/AC ratio is equal to 1.35. For this value, it is predicted that the inverter will operate with an average efficiency of 90.62% and produce 28645 kWh energy for one year.

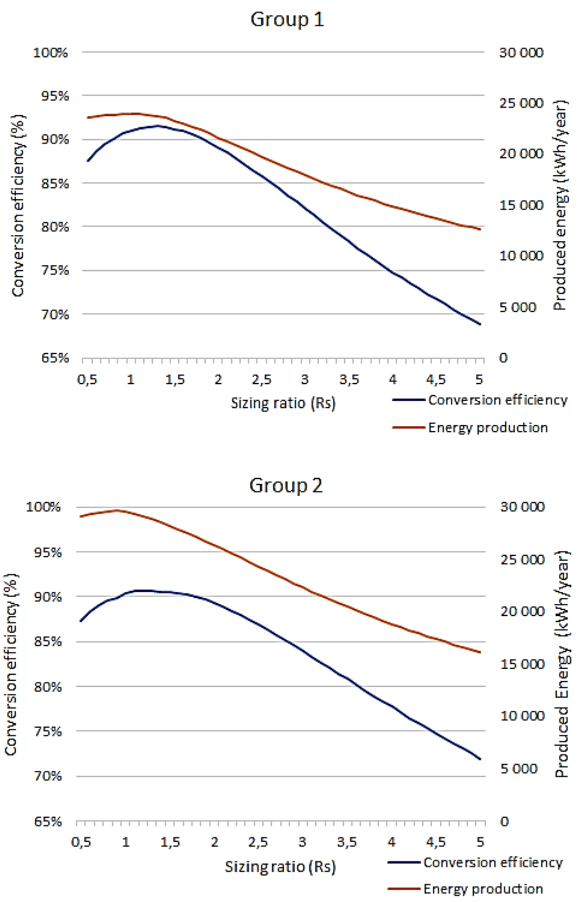

Figure 14. Conversion efficiency and energy productions of groups.

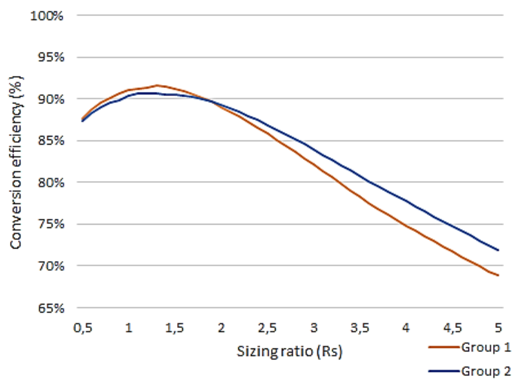

Figure 15. Conversion efficiency of groups

Celal Bayar University Journal of Science
Volume 19, Issue 1, 2023, p 19-29
Doi: 10.18466/cbayarfbe.1200284

In Figure 15, changes in energy conversion efficiency and produced energies according to sizing ratio for Groups 1 and 2 are presented to compare with each other. Although there is a big difference between the energy productions of groups due to the difference in direction, the efficient working range is between 0.5-2 as shown in Figure 15.

4.2. Energy Production Curve Method

This calculation method determines the optimum inverter power by analyzing the hourly energy production of PV panels.

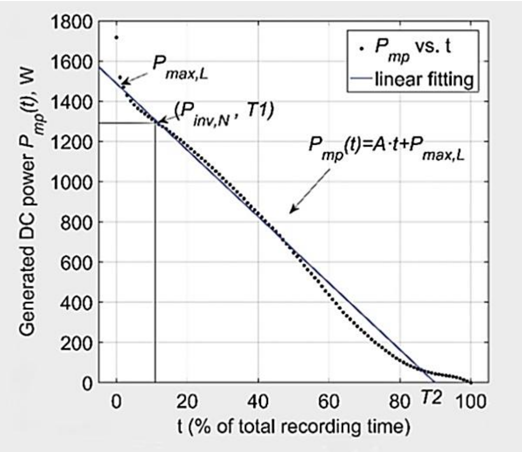

Figure 16. Power duration curve and its linear fitting line.

The first step for the preliminary design of an SPP system with an optimally sized inverter is to create the DC power profile using an appropriate power model with inputs from local climate data. First, the DC energy produced from the irradiance data coming to the panel surface is calculated hourly depending on the direction and angle information. The annual energy production graph is created by placing the produced energy data from high values to low on the time axis. It then offers a suitable realistic inverter sizing based on the DC power-time curve and the line origin intersection of the linear simulation curve.

The DC input instant power of inverter is described in Equation (4). It is the linear fitting line of annual power production graph given in Figure 16.

$$P_{mpp.stc}(t) = A \cdot t + P_{max} \quad (4)$$

The power productions of SPP for Groups 1 and 2 are given for 2020 in Figure 9. Although the power values are the same for the two groups, there is a difference between curves in the graphs for the two groups due to the azimuth angle difference. Linear curves that fit the graphs for the system are calculated and given in Figure 17.

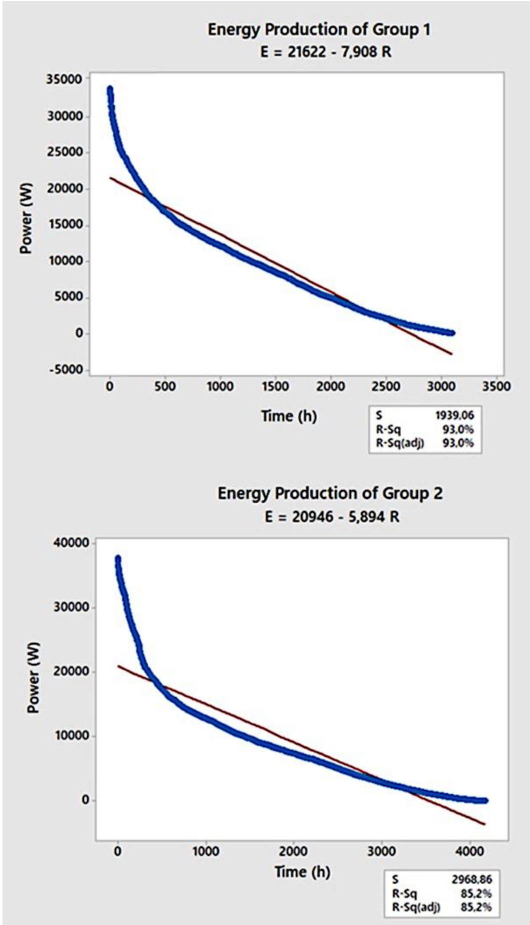

Figure 17. Power duration curve and its linear fitting lines of groups

The parameter values of curves obtained from Figure 17 are given in Table 9. In Equation (4), coefficient A and P_{max} are calculated by using Minitab program.

Table 9. Inverter power equation parameter table for Equation (4).

GROUP	COEFFICIENT A	Pmax (kW)	R^2	R_s
GROUP 1	-7.908	21622	93.0%	1.25
GROUP 2	-5.894	20946	85.2%	1.29

As can be seen from the table, the optimum inverter dimensions are 21622 kW for Group 1 and 20946 kW for Group 2.

When 21622 kW is determined as the optimum inverter power for Group1, the size ratio (R_s) is 1.25. Similarly, the size ratio (R_s) is 1.29 when 20946 kW is determined as the optimum inverter power for Group 2. Depending on the irradiance and angles in SPP location, the DC power value coming to the inverter is lower than DC peak power. It is recommended to choose a lower power inverter for optimum efficiency.

4.3. Comparison Of Optimum Sizing Ratio Calculation Results

The results obtained with both methods, optimum inverter powers, energy conversion ratios and yearly energy productions are compared in Table 10.

For Groups 1 and 2, both methods give close results as given Table 10. If DC/AC ratio is chosen between 1.25 and 1.28, it can be accepted as the optimum value, the system will operate with a clipping loss of about 1%. This result indicates that when inverter power is selected 21000 W for PV power 27000 W. 1% clipping loss will be experienced although the inverter power is reduced by 28%. If DC/AC ratio is chosen between 1.29 and 1.35 for Group 2, it can be accepted as the optimum value, the system will operate with a clipping of about 3-3.7%. This result indicates that optimal value of inverter power is 21000 W for PV power 27000 W. 3-3.7% loss will be experienced although the inverter power is reduced by 28%.

Table 10. Comparison of optimum sizing ratio for calculation

	INVERTER			ENERGY		
	POWER (W)	**DC/AC (-)**	**EFFICIENCY (%)**	**PRODUCED ENERGY (kWh)**	**CLIPPED ENERGY (kWh)**	**LOSS (%)**
EFFICINCY METHOD						
GROUP 1	21094	1.28	91.55%	23747	239	1.0%
GROUP 2	20000	1.35	90.62%	28645	1097	3.7%
ENERGY GRAPH METHOD						
GROUP 1	21622	1.25	93.00%	23789	193	0.8%
GROUP 2	20946	1.29	85.20%	28850	884	3.0%

5. Conclusion

In this study, the effects of the DC/AC ratio, a determining parameter in the inverter selection, in the sizing of an SPP were investigated. The incoming irradiance values of a power plant in Balikesir/Turkey were simulated, and DC energy at the inverter input was calculated. The results obtained from the calculation were compared with the real system production values and were compatible. The effects of the AC/DC ratio on the daily-annual energy production of the system were analyzed numerically and graphically. There are different methodologies to find the optimal value of inverter power. On-grid inverters are usually sized according to the rated power of the PV array. Since solar irradiance varies according to location and meteorological data, the output power of PV panels is also variable. At low solar irradiance levels, the PV array generates less than its rated power. The inverter is operated with lower inverter efficiency. Therefore, calculating the optimal size of the inverter is very important for effective energy production of the PV system. Inverter efficiency is given as a constant in the datasheet, but actually the efficiency decreases rapidly at low power values. The different inverter powers and DC/AC ratios are used to estimate the produced power of a SPP. The high inverter power provides higher system loses and lower clipping loses. Conversely, low inverter power results in lower system losses but higher clipping losses. While sizing the system, if the inverter withlower power is chosen, the transformer power, cable cross-section and connectors dimension will decrease and the system installation cost will also decrease.

As a result of the calculations for the examined SPP, the optimum inverter power for the PV panel system with a DC power of 27000 W was 21000 W, and the size ratio (R_s) was 1.29. When the results for the inverter power 21000 W are examined, it is seen that although the inverter power is reduced by 28%, there will be only 1-3% clipping loss in yearly energy production.

The direction of the installed system affects the amount of energy production. The PV system energy productions are calculated for DC/AC=1 using meteorological data for 2020 and different directions. Program is calculated that change of the system direction will produce the minimum energy 20202 kWh and the maximum energy 30000 kWh. Between the minimum and maximum energy production, there is a 32% difference. This result indicated that the panel's direction was important in selecting inverter power.

The systems operate at maximum power only at certain periods of the year. Systems sized for this situation are forced to operate at lower powers and with lower efficiency throughout the year. Selecting the inverter power for the smallest power that is most efficient for the system while the system is being sized will reduce the installation costs and cross-sections of the system. Since the power panels, conductor sections and substations are sized depending on the inverter power, the inverter power has an important effect on the sizing of the system.

As a result, the effects of inverter power selection and PV panel direction on energy production were studied and analyzed by simulation and real system.

The PV panel direction and inverter power selection are significant parameters to determine the amount of produced energy. Contrary to popular belief, a high-power inverter does not mean more energy generation. A properly sized inverter can make the system more efficient and produce more power, even if it is lower power.

Author's Contributions

Mehmet Fatih Beyoğlu: Drafted and wrote the manuscript, performed the calculation and result analysis.
Metin Demirtaş: Supervised the calculations, result interpretation and helped in manuscript preparation.

Ethics

There are no ethical issues after the publication of this manuscript.

References

[1]. Karafil, A., Ozbay, H., Kesler, M., & Parmaksiz, H., (2016), Calculation of optimum fixed tilt angle of PV panels depending on solar angles and comparison of the results with experimental study conducted in summer in Bilecik, Turkey. ELECO 2015, 971–976, https://doi.org/10.1109/ELECO.2015.7394517.

[2]. Rustemli, S. & Dincadam, F. & Demirtas, M. (2010). Performance comparison of the sun tracking system and fixed system in the application of heating and lighting. *Arabian Journal for Science and Engineering*. 35. 171-183.

[3]. Beyoğlu, M. F. (2011). Comparison of efficiencies of dual axis solar tracking system and fixed axis PV system in Balikesir City. Balıkesir University Institude of Science, Master thesis, https://hdl.handle.net/20.500.12462/2405.

[4]. Beyoğlu, M.F., Demirtaş, M. (2019). A comparative evalution of photovoltaic power plant energy production established in Balikesir province and production forecasting programs. International Marmara Sciences Congress (Autumn) 2019 Proceedings Book (Natural and Applied Sciences), (November), 401–406.

[5]. Abood, A., A. (2015). A comprehensive solar angles simulation and calculation using Matlab. *International Journal of Energy and Enviroment*, 6(4), 367–376, https://doi.org/10.1177/1098214005283748.

[6]. Jazayeri, K., Uysal, S., & Jazayeri, M. (2013). Matlab/Simulink based simulation of solar incidence angle and the sun's position in the sky with respect to observation points on the Earth. Proceedings of 2013 International Conference on Renewable Energy Research and Applications, ICRERA 2013, 173–177, https://doi.org/10.1109/ICRERA.2013.6749746.

[7]. Demoulias, C. (2010). A new simple analytical method for calculating the optimum inverter size in grid-connected PV plants. *Electric Power Systems Research*, 80(10), 1197–1204, https://doi.org/10.1016/j.epsr.2010.04.005.

[8]. Wang, H. X., Muñoz-García, M. A., Moreda, G. P., & Alonso-García, M. C. (2018). Optimum inverter sizing of grid-connected photovoltaic systems based on energetic and economic considerations. *Renewable Energy*, 118, 709–717, https://doi.org/10.1016/j.renene.2017.11.063.

[9]. Faranda, R. S., Hafezi, H., Leva, S., Mussetta, M., & Ogliari, E. (2015). The optimum PV plant for a given solar DC/AC converter. *Energies*, 8(6), 4853–4870, https://doi.org/10.3390/en8064853.

[10]. Pandey, S., Kumar, R., & Panwar, K. (2019). Calculation of inverter power clipping loss due to PV array oversizing. *International Journal of Electrical Engineering and Technology*, 10(4), 43–46, https://doi.org/10.34218/IJEET.10.4.2019.005.

[11]. Camps, X., Velasco, G., de la Hoz, J., & Martín, H. (2015). Contribution to the PV-to-inverter sizing ratio determination using a custom flexible experimental setup. *Applied Energy*, 149, 35–45, https://doi.org/10.1016/j.apenergy.2015.03.050.

[12]. Azzolini, J. A., Reno, M. J., & Horowitz, K. A. W. (2020). Evaluation of curtailment associated with PV system design considerations. IEEE Power and Energy Society General Meeting, 2020-August, https://doi.org/10.1109/PESGM41954.2020.9281427.

[13]. Notton, G., Lazarov, V., & Stoyanov, L. (2010). Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations. *Renewable Energy*, 35(2), 541–554, https://doi.org/10.1016/j.renene.2009.07.013.

[14]. Fernández, F.S., Muñoz-García, M. A., & Saminger-Platz, S. (2016). Detecting clipping in photovoltaic solar plants using fuzzy systems on the feature space. *Solar Energy*, 132, 345–356, https://doi.org/10.1016/j.solener.2016.03.013.

[15]. Deschamps, E.M., & Rüther, R. (2019). Optimization of inverter loading ratio for grid connected photovoltaic systems. *Solar Energy*, 179(November 2018), 106–118, https://doi.org/10.1016/j.solener.2018.12.051.

[16]. Balfour, J., Hill, R., Walker, A., Robinson, G., Gunda, T., & Desai, J. (2021). Masking of photovoltaic system performance problems by inverter clipping and other design and operational practices. *Renewable and Sustainable Energy Reviews*, 145(March), 111067, https://doi.org/10.1016/j.rser.2021.111067.

[17]. Zidane, T. E. K., Zali, S. M., Adzman, M. R., Tajuddin, M. F. N., & Durusu, A. (2021). PV array and inverter optimum sizing for grid-connected photovoltaic power plants using optimization design. Journal of Physics: Conference Series, 1878(1), https://doi.org/10.1088/1742-6596/1878/1/012015.

[18]. Choi, U. M. (2020). Study on Effect of Installation Location on Lifetime of PV Inverter and DC-to-AC Ratio. *IEEE Access*, 8, 86003–86011, https://doi.org/10.1109/ACCESS.2020.2993283.

[19]. Khatib, T., Mohamed, A., Sopian, K., & Mahmoud, M. (2012). An iterative method for calculating the optimum size of inverter in PV systems for Malaysia. *Przeglad Elektrotechniczny*, 88(4 A), 281–284.

[20]. Khatib, T., Yasin, A., Mohammad, A. A., & Ibrahim, I. A. (2017). On the effectiveness of optimally sizing an inverter in a grid-connected photovoltaic power system. 2017 14th International Conference on Smart Cities: Improving Quality of Life Using ICT and IoT, HONET-ICT 2017, 2017-January, 48–52. https://doi.org/10.1109/HONET.2017.8102220.

[21]. Dobos, A. P. (2014). PVWatts Version 5 Manual.