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PRACTICAL AND ESTIMATED EFFICIENCIES OF SOLAR PHOTOVOLTAIC POWER PLANTS

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Abstract: Practical and estimated efficiencies of three (A, B and C) solar photovoltaic power plants (SPVPs) has been determined in this paper. Each of this SPVPs mainly has steel frame constructions for panel placing, polycrystalline silicon type solar PV (photovoltaic) panels, combinations of MPPT (maximum power point tracker) + inverter boxes, collecting busbar, transformer boxes, distributor busbar, kWh meter (output counter), underground cable line and mechanical components for external grid connection, control building, lighting and camera monitoring system. Selected SPVPs were installed in location of Adıyaman City, Türkiye (Latitude: 37.45°, Longitude: 38.17° and Altitude: 672 m), in 2017. Installed power capacity per SPVP is 1.025 MW. The results of the work showed us that the first year average electric energy production is 1691642 kWh and average practical and estimated efficiencies are 15.00% and 14.783%, respectively.

Keywords: Solar PV plant, Practical efficiency, Estimated efficiency

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1. Introduction

Increasing demand and scarcity in conventional sources have triggered the scientist to pave way for the development of research in the field of renewable energy sources especially solar energy (Goura, 2015; Kumar and Sudhakar, 2015).

Renewable energy sources are considered as alternative energy sources due to environmental pollution, global warming and depletion of ozone layer caused by greenhouse effect. Earth receives about 3.8×10^{24} J of solar energy on an average which is 6000 times greater than the world consumption. Solar energy is most readily available source of energy. Solar energy is Non-polluting and maintenance free. Solar energy is becoming more and more attractive especially with the constant fluctuation in supply of grid electricity. Solar power plant is commonly based on the conversion of sunlight into electricity directly using photovoltaic (PV) panel (Aliman et al., 2007; Shukla et al., 2016).

In this work, practical and estimated efficiencies of three 1.025 MW solar photovoltaic power plants (SPVPs) that located in Adıyaman City, Türkiye, has been determined. The results of the work showed us that the first year average electric energy production is 1691642 kWh and average practical and estimated efficiencies are 15.00% and 14.783 %, respectively.

2. Materials and Methods

Three (A, B and C) 1.025 MW solar photovoltaic power plants (SPVPs) has been selected for this work. These SPVPs were installed in location of Adiyaman City, Türkiye (Latitude: 37.45°, Longitude: 38.17° and Altitude: 672 m). Installed power capacity per SPVP is 1.025 MW. Each selected solar photovoltaic power plant mainly has steel frame constructions for panel placing, polycrystalline silicon type solar PV (photovoltaic) panels, combinations of MPPT (maximum power point tracker) + inverter boxes, collecting busbar, transformer boxes, distributor busbar, kWh meter (output counter), underground cable line and mechanical components for external grid connection, control building, lighting and camera monitoring system (Figure 1). In addition, the Current (I) – Voltage (V) curve of the polycrystalline silicon photovoltaic cell (Figure 2), the technical drawings of the polycrystalline silicon photovoltaic module (Figure 3) and the installation angle and direction of the PV panels (Figure 4) are given in Figure 2-4.

Technical specifications of polycrystalline silicon PV module are given in Table 1 and some other technical features regarding the three 1.025 MW solar photovoltaic power plants are also seen in Table 2. As seen from these tables that each PV module has 60 cells, 16.32 % peak efficiency (under STC: Standard Test Conditions: irradiance @ 1000 W/m^2 with an air mass 1.5, module temperature @ 25 °C and @ 0 m/s wind speed), 1.6236 m^2 area, 18.5 kg mass, 45±2 °C nominal operating cell temperature and 97.5%, 90.0%, 80.0% of overall efficiency for first year, 10 years and 25 years, respectively.

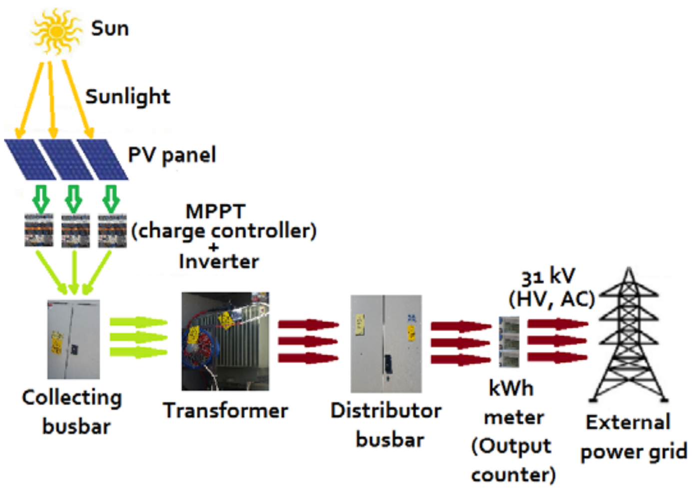

Figure 1. Schematic presentation of working principle of three identical SPVPs.

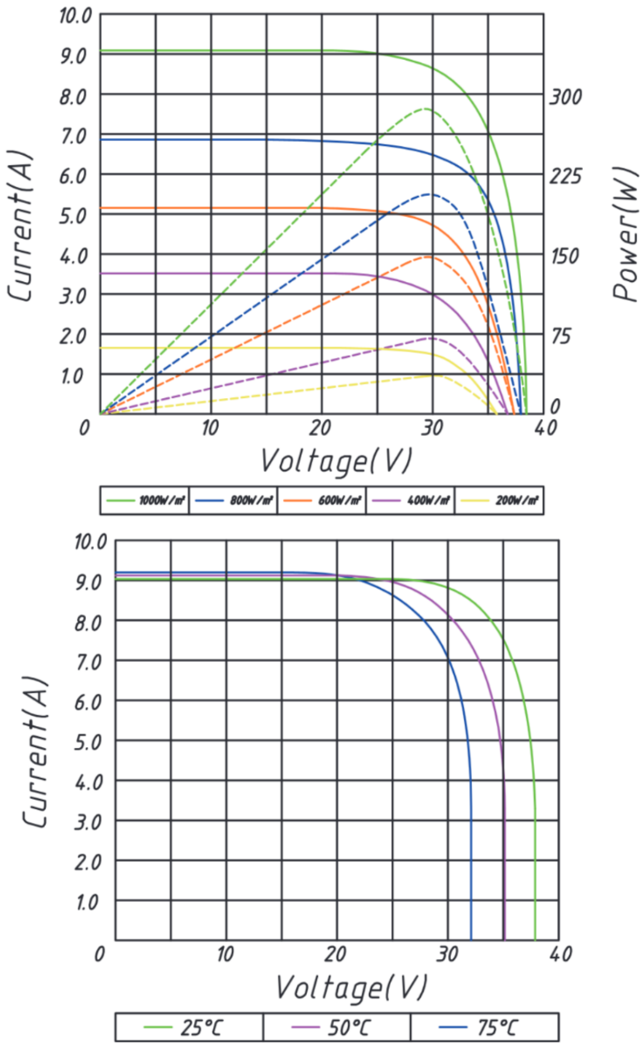

Figure 2. Current (I) – Voltage (V) curve of the polycrystalline silicon photovoltaic cell.

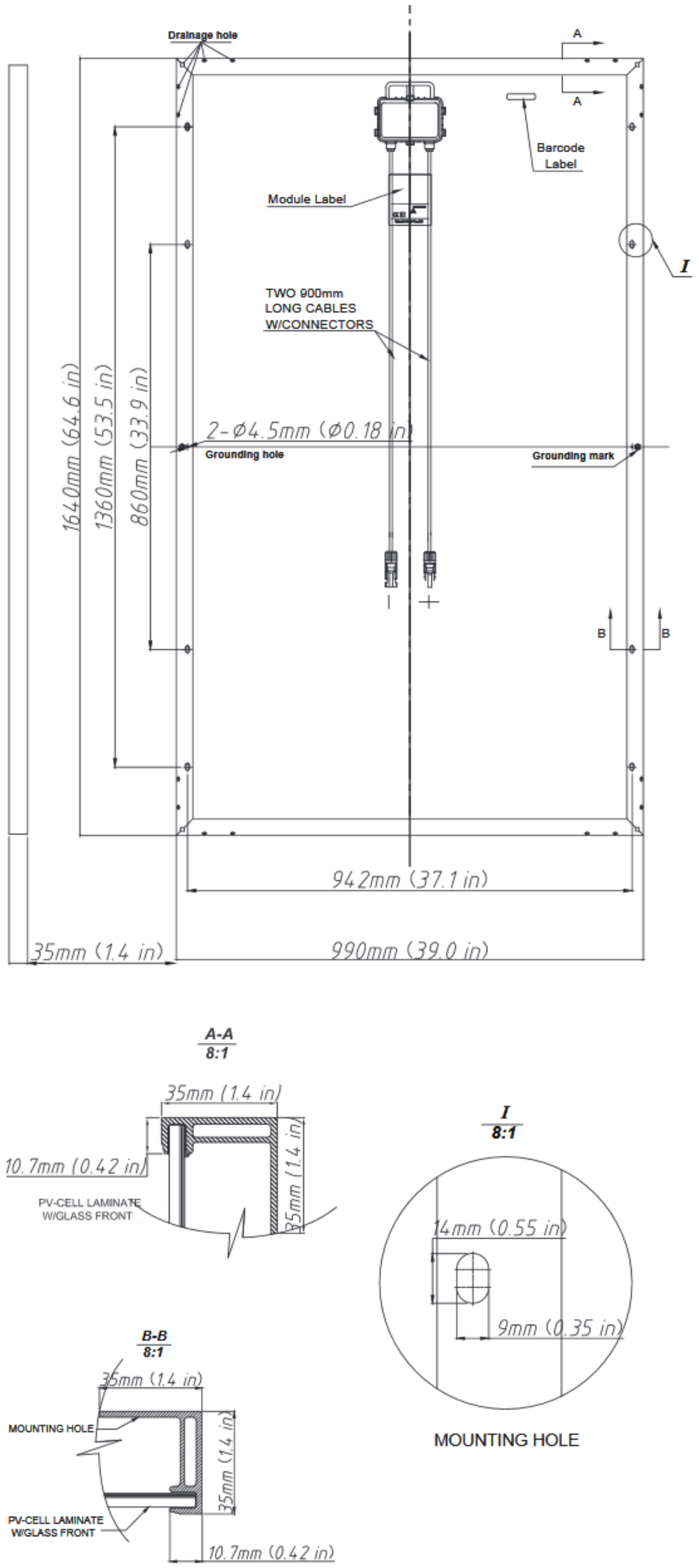

Figure 3. Technical drawings of the polycrystalline silicon photovoltaic module.

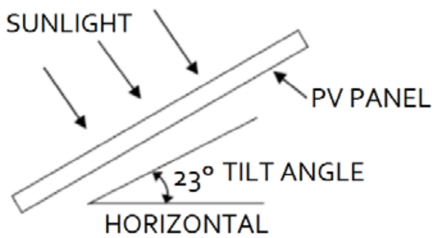

Figure 4. All PV panels were installed at the same orientation and angle.

Besides, it should be noted that the efficiency of solar PV panels are affected by environmental and climatic conditions, temperature, dust and using time (Darwish et al., 2015; Maghami et al., 2016; Costa et al., 2016; Ketjoy and Konyu, 2014; Menoufi et al., 2017; Kumar et al., 2013). In addition to this, other components of the SPVPs such as MPPT, inverter, and transformer has also efficiencies that commonly changing between 95 % … 99 % (Koyuncu, 2017). The maximum possible efficiency of solar panels can also be obtained in first year.

Table 1. Technical specifications of polycrystalline silicon PV module

Type	Polycrystalline silicon
Number of cells	60
Peak efficiency (%)	16.32
Length (mm)	1640
Width (mm)	990
Depth (mm)	35
Module mass (kg)	18.5
STC power rating (Pmax) (W)	265
STC power per unit of area (W/m^2)	163.2
Maximum system voltage (V, DC)	1000
Operating voltage (Vmpp) (V)	30.8
Operating current (Impp) (A)	8.62
Open – circuit voltage (Voc) (V)	37.9
Short – circuit current (Isc) (A)	9.25
Maximum series fuse (A)	15

Table 1. Technical specifications of polycrystalline silicon PV module (continuing)

Type	Polycrystalline silicon
Power tolerance	+ 3%
Operating temperature (°C)	-40 … +85
Nominal operating cell temperature (NOCT) (°C)	45 ± 2
Temperature coefficienct	Pmax : - 0.40 % / °C Voc : - 0.31 % / °C
Front glass	3.2 mm high transmission tempered glass
Frame	Anodized aluminium alloy
Installation method	Rack - mounted
Static loading (Pa)	5400
80% power output warranty period (Year)	25
90% power output warranty period (Year)	10
Workmanship warranty period (Year)	10
Company performance warranty	During the first year, the company guarantees the nominal power output of the product will be no less than 97.5% of the labeled power output. From year 2 to year 24, the nominal power decline will be no more than 0.7% in each year; by the end of year 25, the nominal power output will be no less than 80.7% of the labeled power output.
STC (Standard Test Conditions)	Irradiance @ 1000 W/m^2 with an air mass 1.5 (AM 1.5 g)spectrum, modüle temperature @ 25 °C and @ 0 m/s wind speed

Table 2. Some technical features regarding selected solar photovoltaic power plants

Names of SPVP	A, B, C
Location	Adiyaman City, Türkiye (Latitude : 37,45°, Longitude : 38,17° and Altitude : 672 m)
Installed power capacity per SPVP	1025 MW
Power of each module	265 W
Number of module per SPVP	3868
Total area of panel per SPVP	6280 m^2
Installation cost per SPVP	$ 1000000
Date of commencement of operation	November 27, 2017
PV module type	Polycrystalline silicon
Maximum labeled efficiency of module	$\eta_{MODULE} = 16.32\ \% = 0.1632$
Labeled power output warranty during first year	$\eta_{MODULE-FIRST\ YEAR} = 0.975 \times 0.1632 = 0.15912$
Labeled power output warranty during 10 years	$\eta_{MODULE-10\ YEARS} = 0.90 \times 0.1632 = 0.14688$
Labeled power output warranty during 25 years	$\eta_{MODULE-25\ YEARS} = 0.80 \times 0.1632 = 0.13056$
MPPT and Inverter numbers per SPVP	17
Estimated lifetime of MPPT, inverter and transformer	10 Years
Estimated total efficiency of MPPT, inverter and transformer	$\eta_{MPPT} = 98\ \% = 0.98$ $\eta_{INVERTER} = 98\ \% = 0.98$ $\eta_{TRANSFORMER} = 97\ \% = 0.97$ $\eta_{TOTAL-DEVICE} = 0.98 \times 0.98 \times 0.97 = 0.9316$

Table 2. Some technical features regarding selected solar photovoltaic power plants (continue)

Names of SPVP	A, B, C
Estimated average efficiency due to losses of power cut	Power cut losses = 2 h/Month = 24 h/Year = 1 Day/Year = 1 Day/365 Day = 0.00274 = 0.274 % $\eta_{POWER\ CUT} = 1.00 - 0.00274 = 0.99726$
Estimated average efficiency due to losses of dust (Assume that panels are periodically cleaned)	First year : very less and negligible From year 2 to 25 = 0.5 % = 0.005 $\eta_{DUST} = 99.50$
Estimated system total efficiency	$\eta_{ESTIMATED-SYSTEM-FIRST\ YEAR}$ $= \eta_{MODULE-FIRST\ YEAR}$ x $\eta_{TOTAL-DEVICE}$ x $\eta_{POWER\ CUT}$ $\eta_{ESTIMATED-SYSTEM-FIRST\ YEAR}$ = 0.15912 x 0.9316 x 0.99726 = 0.14783 = 14.783 % $\eta_{ESTIMATED-SYSTEM-10\ YEARS}$ $= \eta_{MODULE-10\ YEARS}$ x $\eta_{TOTAL-DEVICE}$ x $\eta_{POWER\ CUT}$ x η_{DUST} $\eta_{ESTIMATED-SYSTEM-10\ YEARS}$ = 0.14688 x 0.9316 x 0.99726 x 0.9950 = 0.13577 = 13.577 % $\eta_{ESTIMATED-SYSTEM-25\ YEARS}$ $= \eta_{MODULE-25\ YEARS}$ x $\eta_{TOTAL-DEVICE}$ x $\eta_{POWER\ CUT}$ x η_{DUST} $\eta_{ESTIMATED-SYSTEM-25\ YEARS}$ = 0.13056 x 0.9316 x 0.99726 x 99.50 = 0.12069 = 12.069 %

Practical and estimated efficiencies of SPVPs can simply be calculated by using Equations 1 - 5. Practical system total efficiency is equal to annual (first year) generated electric energy divided by annual incident solar energy (Equation 1, 2). Estimated system total efficiency during 10 and 25 years (life time) can also be calculated by using MPPT, inverter, transformer efficiencies and efficiencies due to losses of power cut and dust (Equations 3, 4, 5). The results showed that average practical and estimated efficiencies are 15.00% and 14.783%, respectively, for first year. Both practical and estimated efficiencies are about same and there is negligible differences between them. These data clearly shows that estimated values of efficiencies for 10 and 25 years are quite reliable.

Practical system total efficiency:

$$\eta_{PRACTICAL-SYSTEM}\ (\%) = \frac{E_{GEN}\ (kWh/Year)}{E_{SOL}\ (kWh/Year)} \quad (1)$$

$$E_{SOL}\ (kWh) = I_R\ (kWh/m^2\ x\ Day)\ x\ A_{PV}\ (m^2)\ x\ 365\ (Day/Year) \quad (2)$$

Estimated system total efficiency:

$$\eta_{ESTIMATED-SYSTEM-FIRST\ YEAR}\ (\%) = \eta_{MODULE-FIRST\ YEAR}\ x\ \eta_{TOTAL-DEVICE}\ x\ \eta_{POWER\ CUT} \quad (3)$$

$$\eta_{ESTIMATED-SYSTEM-FIRST\ YEAR} = 0.15912\ x\ 0.9316\ x\ 0.99726 = 0.14783 = 14.783\ \%$$

$$\eta_{ESTIMATED-SYSTEM-10\ YEARS}\ (\%) = \eta_{MODULE-10\ YEARS}\ x\ \eta_{TOTAL-DEVICE}\ x\ \eta_{POWER\ CUT}\ x\ \eta_{DUST} \quad (4)$$

$$\eta_{ESTIMATED-SYSTEM-10\ YEARS} = 0.14688\ x\ 0.9316\ x\ 0.99726\ x\ 0.9950 = 0.13577 = 13.577\ \%$$

$$\eta_{ESTIMATED-SYSTEM-25\ YEARS}\ (\%) = \eta_{MODULE-25\ YEARS}\ x\ \eta_{TOTAL-DEVICE}\ x\ \eta_{POWER\ CUT}\ x\ \eta_{DUST} \quad (5)$$

$$\eta_{ESTIMATED-SYSTEM-25\ YEARS} = 0.13056\ x\ 0.9316\ x\ 0.99726\ x\ 99.50 = 0.12069 = 12.069\ \%$$

where :

$\eta_{PRACTICAL-SYSTEM}$: Practical system total efficiency, %

E_{GEN} : Annual (first year) generated electric energy, kWh

E_{SOL} : Annual incident solar energy, kWh

I_R : Incident solar radiation, kWh/m².Day

A_{PV} : Solar PV panel surface area, m²

$\eta_{ESTIMATED-SYSTEM-FIRST\ YEAR}$: Estimated system total efficiency during first year, %

$\eta_{ESTIMATED-SYSTEM-10\ YEARS}$: Estimated system total efficiency during 10 years, %

$\eta_{ESTIMATED-SYSTEM-25\ YEARS}$: Estimated system total efficiency during 25 years, %

$\eta_{MODULE-1FIRST\ YEAR}$: Labeled power output warranty of the module during first year, 97.5 %

$\eta_{MODULE-10\ YEARS}$: Labeled power output warranty of the module during 10 years, 90 %

$\eta_{MODULE-25\ YEARS}$: Labeled power output warranty of the module during 25 years, 80%

$\eta_{TOTAL-DEVICE}$: Estimated total efficiency of MPPT, inverter and transformer, 93.16%

$\eta_{POWER\,CUT}$: Estimated average efficiency due to losses of power cut, 99.726%

η_{DUST} : Estimated average efficiency due to losses of dust, 99.50%.

3. Results and Discussion

Average solar radiation or solar energy intensity of Adıyaman City, Türkiye for first year and for many years are given in Figure 5 and 6 (Anonymous, 2019). Average values regarding these years are 4.919 kWh/m² Day and 4.941 kWh/m² Day. Both of these data are about same and negligible differences between them. Measured electric energy from kWh-meters for first year and for three SPVP are given in Figure 7. Average measured electricity generation of three SPVPs for first year is 1696665 kWh. Changing of efficiency of polycrystalline silicon module and changing of system sverage efficiency of SPVPs during lifetime are seen in Figure 8 and 9. Average efficiency of polycrystalline silicon module is starting with efficiency of 15.912 % and finishing with 13.443%. Average SPVP system total efficiency is starting with efficiency of 14.783 % and finishing with 12.427 %. Practical system total efficiencies for three 1.025 MW SPVP are given in Figure 10. As seen from this figure that average practical system efficiency and estimated efficiency are 14.783 % and 15.047 % , respectively. Both of these data are about same and negligible differences between them. Labeled efficiency and estimated system total efficiencies for first year, 10 years and 25 years (lifetime) are seen in Figure 11 for comparison. As seen from this figure that data regarding label, first year, 10 years and 25 years (lifetime) are 16.320 %, 14.783 %, 13.577 % and 12.069 %, respectively.

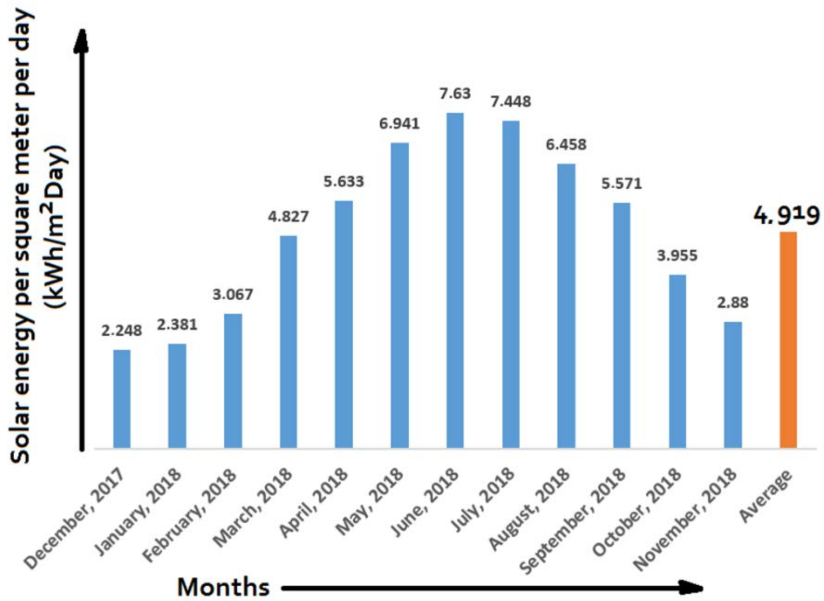

Figure 5. Solar radiation or solar energy intensity of Adiyaman City, Türkiye for first year of SPPs (Anonymous, 2019).

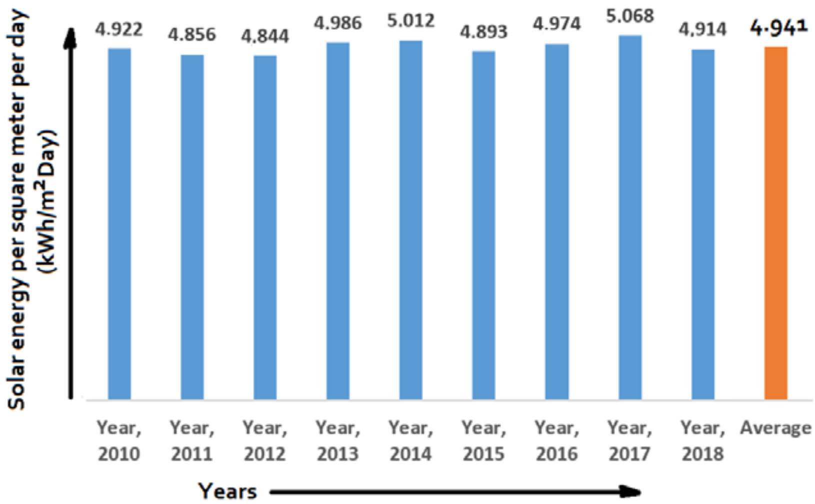

Figure 6. Solar radiation or solar energy intensity of Adiyaman City, Türkiye (Anonymous, 2019).

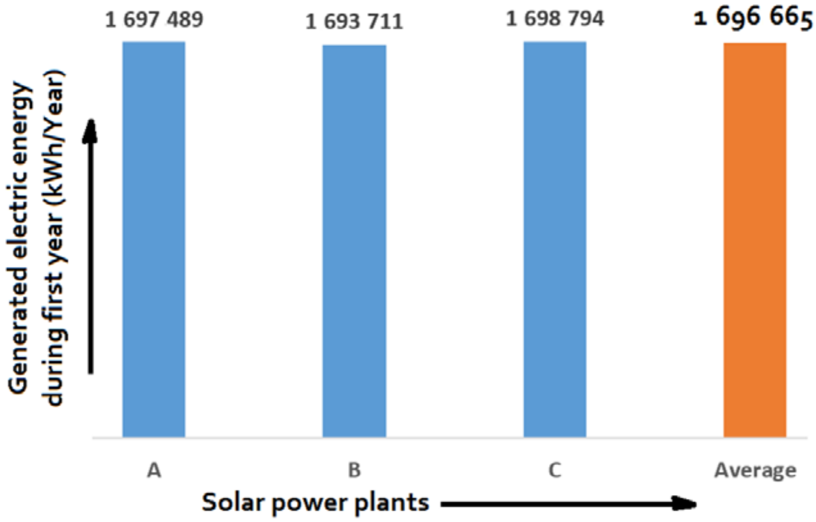

Figure 7. Measured electricity generation of three SPVPs for first year.

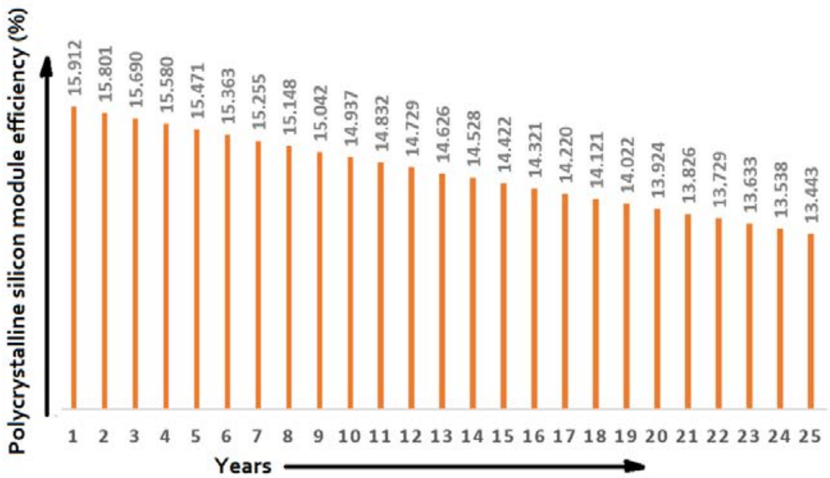

Figure 8. Changing of efficiency of polycrystalline silicon module during lifetime.

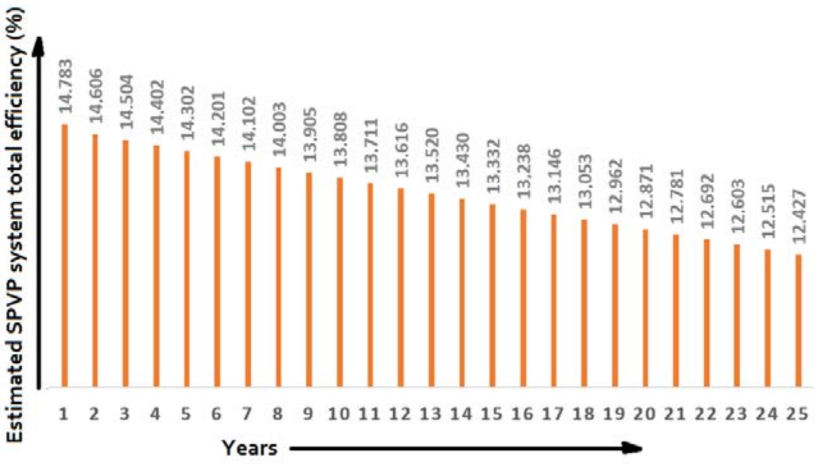

Figure 9. Changing of system total efficiency of SPVPs during lifetime.

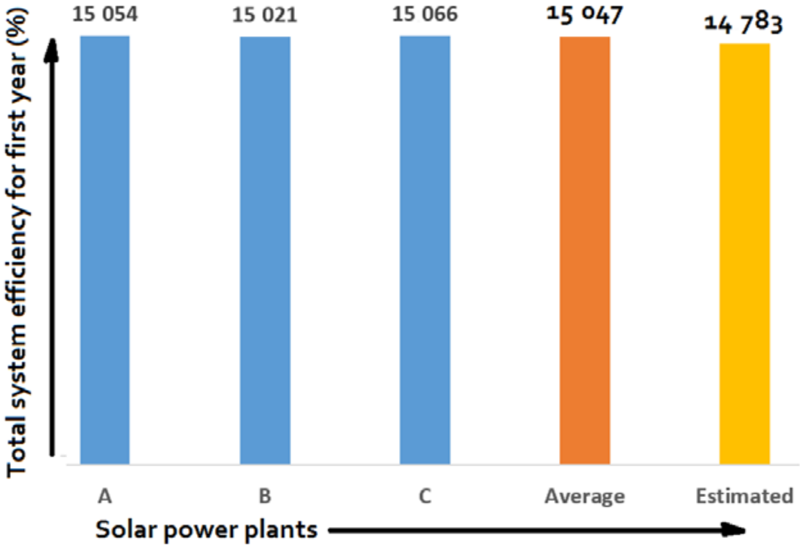

Figure 10. Practical system efficiency for first year.

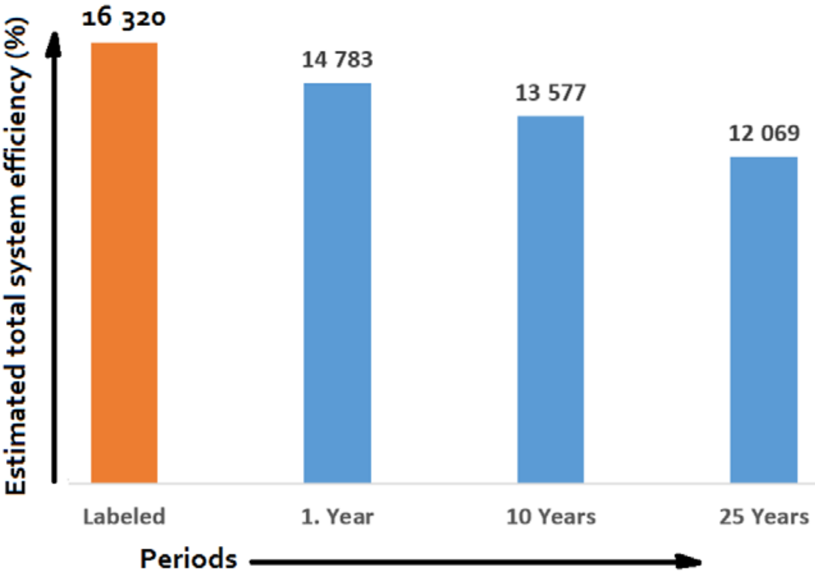

Figure 11. Estimated total system efficiency for first year, 10 years and 25 years (lifetime).

4. Conclusion

Briefly, the results of this work showed us that the average labeled efficiency of polycrystalline silicon module, average practical system efficiency and average estimated system efficiency of these three 1.025 MW SPVPs are 16.320 %, 15.047 % and 14.783 %, respectively for first year. Estimated average system efficiency for 10 years and 25 years (lifetime) are also determined as 13.577% and 12.069 %.

Author Contributions

The percentages of the authors' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	T.K.	F.L.
C	50	50
D	50	50
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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