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Research Article

Comparison of Turkey's Geographical Regions in terms of Stand-Alone PV System Design and Cost Parameters

Nevzat Onat

Faculty of Engineering, Department of Electrical and Electronics Engineering, Manisa Celal Bayar University, Şehit Prof. Dr. İlhanVarank Campus, 45100 Manisa, Turkey

Correspondence should be addressed to Nevzat Onat; nevzat.onat@cbu.edu.tr

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Stand-alone photovoltaic (SAPV) systems are widely used in rural areas where there is no national grid or as a precaution against power outages. In this study, technical and economic analysis of a SAPV system was carried out using meteorological data for 75 province centers in seven geographical regions of Turkey. Obtained results for each province center were separated by geographical area. The averages of the centers for each region are taken as output. A calculation algorithm based on MsExcel has been established for these operations. The analyses made with the developed algorithm are repeated for five different scenarios that they cover periods of time when a constant strong load is active for all seasons (winter, spring, summer, and autumn) and all year round. The developed algorithm calculates the life-cycle cost, the unit energy cost, the electrical capacity utilization rate, the amount of generated/excess energy per month, the initial investment/replacement, and operating and maintenance (O&M) costs of each element. As a result, geographical regions of Turkey are compared in terms of these outputs graphically. Further investigations may include the sale of excess energy generated, small-scale PV system cost factors parallel to the grid, and the effects of government incentives.

1. Introduction

Stand-alone photovoltaic (SAPV) systems are one of the best options for energy conversion, especially in areas where there is no national grid. Establishing small-scale stand-alone wind farms is often technically and economically disadvantageous. The efficiency of small-scale wind turbines is relatively low. The operating and maintenance (O&M) difficulties caused by the installation in the remote areas are also the most important deficiencies due to more failures than PV systems because of moving parts. Because of these reasons, PV systems with a quick settling time, long life, and lower risk of failure are preferred. SAPV systems typically have installed powers between 0.5 kW and 20 kW [1]. They can supply loads such as rural homes, homes or surveillance centers for various purposes in forested areas, telecom radar stations, irrigation pumps, and lighting devices. Figure 1 shows SAPV system components. Since SAPV systems are completely independent of the interconnected grid, apart from the PV panels consisting of multiple modules, the storage component and the charge regulator are indispensable equipment. Photovoltaic panels are the most important component of the system. Factors affecting the performance of PV modules are examined in detail in [2]. The battery pack performs storage when the PV surface generates more energy than what the load needs. Otherwise, it starts feeding the load. In SAPV systems, the daily load can be taken as constant. The charging and discharging times of the batteries used in these systems are also dependent on the atmospheric conditions. In the case of low sunshine, the amount of energy drawn from the PV array will be reduced. In this case, the batteries will discharge faster [3]. These conditions can adversely affect the efficiency and life cycle of batteries. For this reason, the battery model should be determined considering the seasonal conditions. The most important waste material of SAPV systems is also the battery unit [4]. Therefore, excessive use of the battery makes the environmental impact of the system more negative.

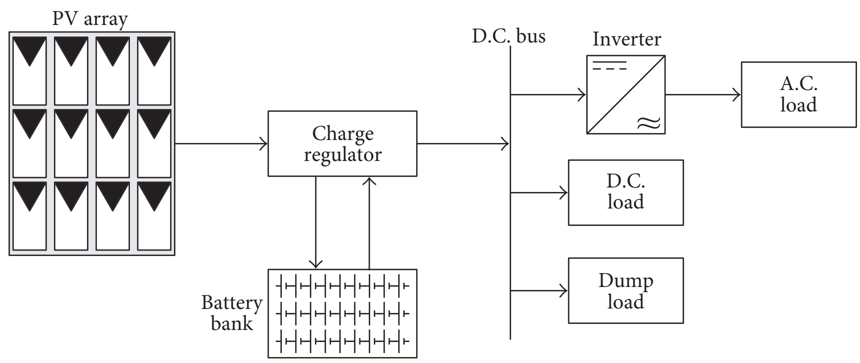

Figure 1: Basic components of SAPV plant.

In the economic analysis of these systems, the future costs of initial investment and recurrent purchases of fixed components of the project are also taken into account. This process is generally called life-cycle cost analysis (LCC). In this analysis, inflation and discount rates of the country are very effective. Therefore, the unit energy cost (UEC) of the system is also related to these ratios [5, 6].

2. Material and Method

Al-falahi et al. have recently categorized the methods of designing and dimensioning SAPV used in today's comprehensive review under three headings as classical, modern, and computer software [7]. Intuitive, numerical, and analytical methods are used separately or hybrid in the design and cost analysis of SAPV systems. Commercial computer software and artificial intelligence techniques (categorized as modern methods in [7]) can be used especially for the analysis of meteorological data. HOMER, HYBRID2, HOGA, and PHOTOV-III are the most widely used commercial software [8]. In SAPV designs, meteorological data and load demand values can be used by considering daily or monthly averages [1, 9]. In this section, the path that is followed in sizing and determining the cost of all the equipment that makes up the designed SAPV system is explained. The most important factors in the installation of SAPV power plant are the location of the system, the operating voltage of the load, the geographical conditions, and how long the load must remain active. These parameters are influential on the basic component's sizing such as panels, batteries, regulators, inverters, and converter. Naturally, they also determine the cost of these equipments and the costs of balance of system (BOS) and O&M. For this reason, scenarios have been produced to predict the operation of SAPV systems in different seasons. With this approach, technical and economic analyses were made for five different time intervals. In four scenarios, the load is only active for one season. In the 5th scenario, continuous operation is considered throughout the year. The parameters of the system are determined and given in Table 1.

Table 1: Constant values of SAPV system components.

Life cycle (years)	System	25
	Module	25
	Battery	10
	Charge regulator	15
Operating period (months)		12
Annually operating days*		365
Annually operating hours*		8760
Load power (VA)		1000
Module current (A)		22.5
Battery voltage (V)		12
Battery capacity (Ah)		110
Efficiency	Battery	0.95
	Transmission line	0.98
Unit price ($)	Module	200
	Battery	150
	Charge regulator	100
Daily load demand	(Ah/day)	2148.23
	(kVAh/day)	25.78
Replacement numbers	Module	0
	Battery	2
	Charge regulator	1
Annual inflation rate		0.12
Annual discount rate		0.18

*These values vary according to the selected scenario. The values in the table are given for the whole year scenario.

Here, it is assumed that the electrical charge is fed by direct current. In the case of the load fed by the alternating current, for the inverter, variables such as efficiency, initial investment cost, and change numbers should be included in the calculation. The purpose of the study is to examine the changes in energy costs according to geographical regions. For this reason, the inverter and/or converter costs will have approximately the same effect as constant parameters for all geographic region calculations.

In the next step, the components of the SAPV system can be determined and cost calculations can be made. First, it is necessary to determine the number of battery and PV modules that change depending on the load rated power and the system location. The load demand (D.C.) is determined by

$$\sum L = \left[\frac{S_L \cdot n_{hour}}{n_{day} \cdot V_b \cdot \eta_w \cdot \eta_b} \right]. \quad (1)$$

The number of storage days, the required battery capacity, and the number according to the selected battery type can be calculated by (2), (3), and (4), respectively. In the selected scenario, the minimum peak sun hour value is considered as T_{min}.

$$n_{SD} = -0.48 \cdot T_{min} + 4.58, \quad (2)$$

$$\sum C_B = \sum L \cdot \left(\frac{n_{SD}}{D_T \cdot D_{ch} \cdot (\text{disch})} \right), \quad (3)$$

$$n_B = \frac{\sum C_B}{C_B}. \quad (4)$$

Practically $D_T \cdot D_{ch} \cdot (\text{disch}) \cong 0.8$ is assumed [10, 11]. In this study, the value calculated from (2) for some regions can be zero or negative. Especially in the summer scenario, the number of batteries for zero and negative values in the calculations is directly taken as "1". After this step, PV array sizing can be done by taking the current value from the selected PV module tag. Here, a 270 W monocrystalline PV module with 12 V rated voltage and a current rating of 22.5 A was selected. The total current drawn from the PV array to be formed by these modules and accordingly the number of modules required is calculated by the following equations:

$$I_{PV} = \frac{\sum L}{T_{min} \cdot 0.9}, \quad (5)$$

$$n_M = \frac{I_{PV}}{I_M}. \quad (6)$$

In (5), a correction factor (0.9) was used, taking into account the effects of dirt accumulation on the crystalline module, daytime temperature and sun angle changes [10]. The charge regulator, which is the other component of the system, is selected so that it can control the maximum current value. In addition, other complementary equipment's of the system (fuses, fuse holders, sockets, switches, protection systems, grounding rods, battery houses, electrical panels, etc.) should also be considered in the design phase. The cost of these elements is called the BOS cost. The BOS price is initial investment component and it is practically taken as 10% of the total PV array cost [10].

With (1), (2), (3), (4), (5), and (6), the design features of the stand-alone PV system have been determined. By determining the initial investment costs of all equipment to be used in the system, the total life cost can be calculated by the following equations. In addition to the initial installation and design costs, the costs of O&M and replacement have also been added.

As is known, the present worth factor of an item that will be bought after "n" years is given as

$$P_R = \left(\frac{1+i}{1+d} \right)^n. \quad (7)$$

In this case, the present worth of a purchase in the nth year can be calculated with

$$P_{Worth,n} = P_R \cdot C_0. \quad (8)$$

The present worth of recurring purchases is also given as

$$\sum P_{Worth} = C_0 + C_0 \left(\frac{1+i}{1+d} \right) + C_0 \left(\frac{1+i}{1+d} \right)^2 + C_0 \left(\frac{1+i}{1+d} \right)^3 + \cdots + C_0 \left(\frac{1+i}{1+d} \right)^{n-1}. \quad (9)$$

Equation (9) requires that the components such as the battery, charge regulator, and module need replacement after several years depending on their service life [12]. In addition, O&M costs of the system have to be taken into account as a recurring purchase every year. In this study, since the system life is determined as 25 years, it is predicted that the modules will not need replacement. O&M costs are assumed to be 5% of the total investment cost of the PV array. In some studies, this value can be taken as 1% of the total initial investment cost of SAPV system [13].

In this case, the LCC will be equal to the sum of the total present worth of each component. Initial investment, O&M, and replacement costs are essential components of LCC analysis. In many studies, (10) is given for LCC [14–16].

$$\text{LCC} = C_0 + C_{\text{O\&M}_{\text{PWorth}}} + C_{\text{R}_{\text{PWorth}}}. \quad (10)$$

In some literature examples, salvage cost is added negatively to (10) [5, 17–19]. This value can be defined as the income to be obtained by dismantling and selling after the system has completed its economic life.

In a SAPV system, total energy production is directly related to the PV array. Here, monthly energy generation will vary depending on the minimum peak sun hours. Monthly calculation results with developed algorithm are collected to obtain the annual energy production amount. Equation (11) can be used for the daily energy production of the PV array. The total amount of energy that the PV system will generate over its lifetime is given by (12). Equation (12) calculates the amount of energy in kVAh. Here, the efficiency reductions in the PV modules over the years have been neglected.

$$W_{PV} = n_M \cdot I_M \cdot T_{min}, \quad (11)$$

$$W_{LC} = \frac{W_{PV} \cdot V_b \cdot n \cdot n_{day}}{1000}. \quad (12)$$

The demand energy by the load is obtained from

$$W_L = \frac{\sum L \cdot V_b \cdot n \cdot n_{day}}{1000}. \quad (13)$$

Table 2: Average sun hours of Turkey's provinces [26].

Geographical region	Provinces	Average sun hours (hour/day) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Marmara	Balikesir	4.05	5.05	5.92	7.26	9.23	10.99	11.44	10.65	8.84	6.53	4.69	3.64
	Bilecik	3.31	4.45	4.77	6.27	8.75	9.86	10.48	9.75	8.48	5.86	4.44	3.31
	Bursa	3.71	4.51	5.64	6.96	8.90	10.11	10.78	9.98	8.49	5.84	4.35	3.40
	Çanakkale	4.21	5.50	6.28	7.77	9.54	11.56	11.85	11.01	9.00	6.81	4.93	3.83
	Edirne	3.93	5.31	5.94	7.69	9.54	10.96	11.73	10.71	8.88	6.03	4.56	3.37
	Istanbul	3.46	4.43	5.32	6.85	8.61	10.51	11.17	10.14	7.83	5.22	3.85	2.96
	Kirklareli	3.68	5.09	5.43	7.37	8.93	11.47	12.50	11.23	8.30	5.32	4.22	2.87
	Kocaeli	3.29	4.17	5.20	6.55	8.56	9.79	10.44	9.59	7.96	5.40	3.95	3.06
	Sakarya	3.20	4.23	5.01	6.33	8.39	9.72	10.35	9.56	8.01	5.53	4.05	3.09
	Tekirdağ	3.69	4.96	5.54	7.26	9.05	11.21	11.92	10.93	8.32	5.66	4.15	3.13
	Yalova	3.27	4.25	5.41	6.84	8.78	9.96	10.70	9.75	8.15	5.53	4.05	3.04
Aegean	Afyon	3.91	5.17	5.64	7.05	9.27	10.71	11.36	10.73	9.39	6.82	5.12	3.74
	Aydin	5.16	5.98	7.00	8.09	9.76	11.79	12.09	11.45	9.85	7.67	5.76	4.45
	Denizli	4.88	5.75	6.86	7.90	9.64	11.36	11.83	11.19	9.73	7.35	5.61	4.23
	Izmir	4.86	5.86	6.96	8.03	9.77	11.89	12.20	11.48	9.67	7.61	5.55	4.27
	Kütahya	3.71	4.78	5.50	6.65	8.91	10.29	10.77	10.09	8.90	6.26	4.75	3.51
	Manisa	4.60	5.45	6.57	7.62	9.49	11.32	11.77	11.06	9.26	7.11	5.22	3.94
	Muğla	5.13	6.20	7.12	8.18	9.91	11.73	11.90	11.31	9.92	7.85	6.01	4.67
	Uşak	4.60	5.33	6.46	7.48	9.37	10.83	11.42	10.76	9.38	6.93	5.14	3.98
Mediterranean	Adana	4.67	5.65	6.97	7.84	9.72	11.29	11.77	11.22	10.15	7.78	5.86	4.21
	Antalya	4.95	6.10	7.24	8.29	9.70	11.55	11.84	11.29	9.80	7.68	5.97	4.55
	Burdur	4.74	5.82	6.98	7.97	9.61	11.40	11.85	11.25	9.78	7.45	5.72	4.23
	Hatay	5.09	6.22	7.17	8.28	10.23	11.14	10.89	10.47	9.80	7.86	6.37	4.99
	Isparta	4.38	5.46	6.82	7.77	9.42	11.10	11.70	11.13	9.64	7.17	5.44	3.95
	Kahramanmaraş	4.21	5.47	6.61	7.85	9.57	11.49	12.07	11.43	10.13	7.55	5.56	3.86
	Mersin	4.99	6.04	7.35	8.38	9.94	11.18	11.45	11.03	10.02	7.91	6.15	4.64
Black Sea	Amasya	3.57	4.65	5.48	6.60	8.16	9.58	10.14	9.70	8.11	6.11	4.51	3.19
	Artvin	3.49	4.13	5.56	6.61	7.12	8.10	7.65	7.64	6.86	5.38	4.27	3.14
	Bartin	3.31	4.30	5.29	6.66	7.81	9.94	10.79	9.94	7.64	5.41	4.08	2.96
	Bolu	3.28	4.41	5.19	6.53	8.31	9.73	10.44	9.74	8.15	5.78	4.26	3.12
	Çorum	3.60	4.79	5.92	6.99	8.29	9.91	10.66	10.16	8.32	6.19	4.57	3.21
	Düzce	3.17	4.25	5.20	6.37	8.21	9.71	10.40	9.67	7.96	5.60	4.03	3.04
	Gümüşhane	3.02	4.60	5.54	6.74	8.17	9.25	9.30	8.99	8.28	5.95	4.43	2.99
	Kastamonu	3.39	4.44	5.45	6.65	7.86	9.82	10.66	9.87	7.67	5.58	4.26	3.10
	Ordu	3.44	4.40	4.77	6.24	7.96	9.06	8.92	8.60	7.72	5.80	4.34	3.11
	Rize	3.38	4.21	5.21	6.40	7.47	8.19	7.75	7.54	7.19	5.37	4.17	3.02
	Samsun	3.60	4.41	5.17	6.43	7.92	9.15	9.52	8.97	7.61	5.72	4.32	3.22
	Sinop	3.46	4.42	5.35	6.62	7.80	9.44	10.08	9.32	7.57	5.56	4.32	3.21
	Tokat	3.60	4.72	5.50	6.71	8.27	9.74	10.12	9.79	8.40	6.33	4.62	3.20
	Trabzon	3.17	4.29	4.88	6.16	7.64	8.35	7.90	7.62	7.43	5.42	4.20	2.99
	Zonguldak	3.27	4.25	5.37	6.62	8.10	9.83	10.59	9.79	7.84	5.54	4.02	3.07
Central Anatolia	Ankara	3.73	4.89	6.16	7.21	8.76	10.21	11.06	10.45	8.83	6.48	4.73	3.35
	Aksaray	4.11	5.40	6.80	7.97	9.36	11.27	12.12	11.53	9.81	7.36	5.45	3.73
	Çankiri	3.69	4.75	6.24	7.08	8.27	9.90	10.70	10.09	8.23	6.05	4.47	3.21
	Karaman	4.46	5.85	7.14	8.44	9.84	11.51	12.02	11.47	10.11	7.77	5.95	4.31
	Kayseri	4.08	5.31	6.37	7.59	9.21	11.22	12.03	11.47	9.84	7.39	5.39	3.55
	Kirikkale	3.79	4.99	6.57	7.48	8.66	10.32	11.17	10.63	8.84	6.57	4.76	3.31

Table 2: Continued.

Geographical region	Provinces	Average sun hours (hour/day) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Kirşehir	3.97	5.18	6.61	7.72	9.02	10.78	11.73	11.15	9.32	6.98	5.07	3.51
	Konya	4.19	5.51	6.88	8.03	9.46	11.28	11.97	11.35	9.79	7.35	5.53	3.93
	Niğde	4.41	5.48	6.74	7.85	9.51	11.39	12.16	11.57	10.06	7.61	5.65	3.90
	Nevşehir	4.07	5.32	6.43	7.65	9.16	11.17	12.05	11.48	9.68	7.27	5.35	3.57
	Sivas	3.76	5.02	5.99	7.20	8.73	10.50	11.09	10.65	9.23	6.80	4.97	3.30
	Yozgat	3.80	5.12	6.10	7.29	8.72	10.60	11.41	10.92	9.10	6.85	4.99	3.33
Eastern Anatolia	Ağri	4.10	5.43	6.25	7.62	9.08	10.82	11.32	10.79	9.45	7.14	5.42	3.96
	Ardahan	3.75	4.31	6.01	6.93	7.12	8.76	8.85	8.94	7.33	5.90	4.68	3.42
	Bingöl	4.08	4.93	6.02	7.18	9.08	11.01	11.51	10.87	9.54	6.87	4.89	3.45
	Bitlis	3.46	4.72	5.56	7.13	9.27	10.95	11.31	10.62	9.81	6.86	5.19	3.59
	Elaziğ	4.13	5.14	6.37	7.56	9.39	11.45	12.01	11.33	9.86	7.14	5.12	3.56
	Erzincan	3.73	4.85	6.15	7.14	8.63	10.29	10.67	10.23	9.12	6.52	4.71	3.27
	Erzurum	3.85	4.71	5.82	6.95	8.28	9.86	10.30	9.91	8.50	6.24	4.57	3.31
	Hakkari	6.65	8.17	8.92	9.95	11.31	12.71	12.61	11.85	10.70	8.69	7.42	6.42
	Iğdir	5.88	7.34	8.43	9.64	10.87	12.34	12.59	11.65	10.25	8.33	6.86	5.61
	Kars	3.82	4.74	6.24	7.04	7.90	9.89	10.55	10.36	8.15	6.46	4.82	3.44
	Malatya	4.23	5.30	6.59	7.86	9.41	11.43	12.09	11.44	9.96	7.28	5.26	3.64
	Muş	3.66	4.80	5.56	7.25	9.13	10.83	11.42	10.76	9.60	6.89	4.98	3.47
	Tunceli	4.02	4.99	6.25	7.27	9.00	10.88	11.43	10.86	9.49	6.85	4.88	3.41
	Van	5.27	6.40	7.39	8.50	10.11	11.55	11.65	10.97	10.31	7.65	6.16	4.93
Southeastern Anatolia	Adiyaman	4.51	5.49	6.74	8.08	9.70	11.78	12.25	11.52	10.17	7.56	5.56	4.01
	Batman	3.92	5.02	6.16	7.64	9.71	11.72	12.09	11.34	10.05	7.33	5.48	3.92
	Diyarbakir	3.73	4.89	6.16	7.21	8.76	10.21	11.06	10.45	8.93	6.48	4.73	3.35
	Gaziantep	4.60	5.78	6.82	8.10	9.93	11.63	11.74	11.07	10.03	7.80	5.98	4.38
	Kilis	4.70	5.92	6.80	8.12	10.15	11.48	11.43	10.86	9.81	7.86	6.14	4.58
	Mardin	4.35	5.45	6.74	7.90	10.01	12.52	12.84	12.03	10.07	7.59	5.83	4.43
	Siirt	3.84	5.00	6.04	7.38	9.64	11.52	11.78	11.07	9.99	7.19	5.53	4.02
	Şanliurfa	4.68	5.62	6.92	8.14	9.96	12.24	12.42	11.66	10.11	7.71	5.87	4.40

After this step, the capacity utilization rate (CUR) and unit energy cost (UEC) can be calculated by (14) and (15), respectively:

$$\mathrm{CUR} = \frac{W_{\mathrm{L}}}{W_{\mathrm{LC}}}, \tag{14}$$

$$\mathrm{UEC} = \frac{\mathrm{LCC}}{W_{\mathrm{L}}}. \tag{15}$$

The above equations have been applied using meteorological data for 75 provincial centers of seven geographical regions in Turkey. The values obtained from the averages of provincial centers constituting each region were categorized and tabulated for each region to compare graphically. For this, an Excel-based calculation algorithm is established. The developed algorithm was applied to five different scenarios. In these scenarios, the load is assumed to be seasonal (spring, summer, autumn, and winter) and continuous service throughout the year. The calculation results and graphics given in the next section are also based on this supposition. Thus, the effects of seasonal climate changes on the cost factors of stand-alone PV systems as well as geographical regional differences have been examined. Table 2 gives the monthly average sun hours for 75 centers and what geographical regions they represent. The flowchart of the developed algorithm is also shown in Figure 2.

3. Results and Discussion

3.1. Life-Cycle Cost Analysis. As mentioned above, calculations are made for five different scenarios. Table 3 gives an example of the calculation results for the scenario where the load is active all year round. In the all-year scenario, there are regional differences in initial investment costs and also LCCs. However, differences between the produced energy amounts are lower. In terms of CURs, the values in Table 3 are calculated taking into account the total energy generated in each province center that constitutes the geographical region. Thus, the results obtained from (14) also include the differences between the provinces of the geographical

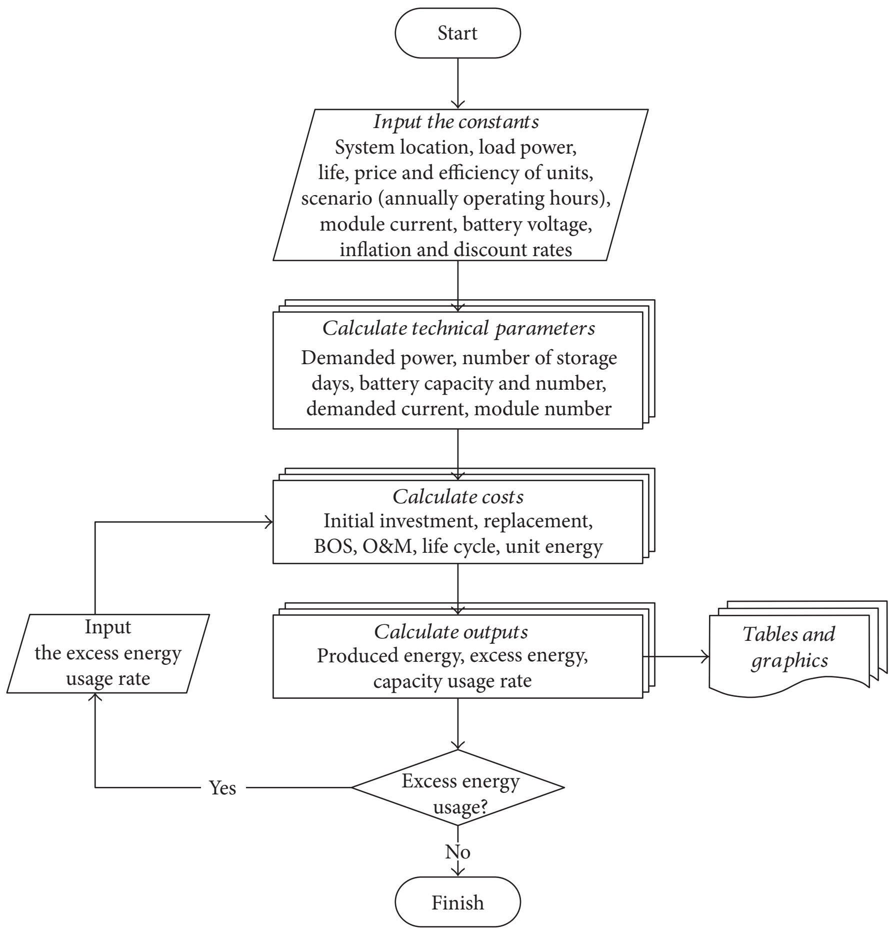

Figure 2: Flowchart of the calculation algorithm.

regions. The developed algorithm calculates the values shown in Table 3 for each province center. In the next step, the results are given by taking the averages according to the geographical region classifications shown in Table 2. The decimal part of the number of calculated modules is always rounded up. The battery number can be rounded up or down by the designer, taking into account factors such as installation conditions and load criticality [10].

In all-year, winter, spring, and autumn scenarios, storage costs are 64% of LCC. 19% of the LCC is module cost. The remaining 17% is the sum of the charge regulator, BOS, and O&M costs. These ratios show very important differences only in the summer scenario. The share of storage costs within the total LCC is about 1% in summer. Module and O&M cost ratios are 49% and 36%, respectively. In particular, the effects on the replacement costs of inflation and discount rates in the country are particularly important. In [16], the inflation and the discount rates are taken as 4% and 5%, respectively, in the SAPV design for a residential consumer in Malaysia. In the LCC analysis conducted under these conditions, the shares of the module and battery costs in the total LCC were 32% and 38%, respectively. The system life is also taken as 20 years. Taking into consideration that this study is accepted for 25 years, it can be said that the share of battery at lifetime cost will be even higher.

Figure 3 shows the results obtained from the LCC calculations of the SAPV system. For winter and all-year scenarios, LCCs are equal, because the values of the worst sun hours for both periods are the same. In general, the most disadvantaged geographical area in terms of LCC is the Black Sea Region. However, it can be said that the Marmara and the Black Sea Region's LCC values are closer to each other, especially for spring and autumn scenarios. The highest initial investment cost in the autumn scenario is in the Marmara region. In all scenarios, the Aegean and Mediterranean regions have the most advantageous LCC values and these values are very close to each other. The difference between the highest (Black Sea, LCC = $34,790.57) and the lowest (Aegean, LCC = $26,148.64) geographical regions is around 25% in all-year and winter scenarios. In the spring scenario, the difference between the lowest (Mediterranean, $14,360.8) and the highest (Black Sea, $21,883.58) LCCs was 34.4%. These differences were 30.5% and 28.7% in the summer and autumn scenarios, respectively.

3.2. Unit Energy Cost Analysis. Figure 4 shows the cost of unit energy, one of the most important economic indicators of a power plant. The most important factors on the UEC are the life of the system, the replacement periods of equipment's used in the system, the sale of excess energy, inflation, and

Table 3: Calculations for the all-year (8760 hours) scenario.

Parameter		Marmara	Aegean	Mediterranean	Black Sea	Central Anatolia	Eastern Anatolia	Southeastern Anatolia
		Regions						
Total battery size (Ah)		8115.42	6562.84	6695.41	8296.89	7679.91	7190.73	6967.24
Battery number*		71.97	59.66	58.49	74.31	61.30	69.74	64.82
Modified design current (A)		740.80	536.39	553.04	769.42	670.96	628.42	582.23
Module number**		32.92	23.84	24.58	34.20	29.82	27.93	25.88
Initial investment costs ($)	Module	6672.23	4800.00	5028.57	6960.00	6066.67	5685.71	5300.00
	Battery	11,004.55	8850.00	9064.29	11,260.00	10,412.50	9750.00	9142.50
	Charge regulator	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	BOS	667.27	480.00	502.60	696.00	606.67	568.57	530.00
	O&M	333.64	240.00	251.43	348.00	303.63	284.29	265.00
	Total	**18,778.20**	**14,470.00**	**14,947.10**	**19,364.00**	**17,489.20**	**16,388.20**	**15,607.50**
LCC costs ($)	Module	6672.73	4800.00	5028.57	6960.00	6066.67	5685.71	5300.00
	Battery	21,410.02	17,218.22	17,365.12	21,907.02	20,258.16	18,969.22	18,312.60
	Charge regulator	145.71	145.71	145.71	145.71	145.71	145.71	145.71
	BOS	667.27	480.00	502.86	696.00	606.67	568.57	530.00
	O&M	4872.08	3504.71	3671.61	5081.84	4429.57	4151.42	4782.47
	Total	**33,767.81**	**26,148.64**	**26,983.87**	**34,790.57**	**31,506.77**	**29,520.64**	**29,070.78**
Lifetime total energy (to be produced) (MVAh)		7448.87	6802.37	6831.41	6989.77	7328.96	6723.80	6970.57
Lifetime total energy (to be consumed by load) (MVAh)		235.23	235.23	235.23	235.23	235.23	235.23	235.23
The capacity utilization rate (%)		3.16	3.46	3.44	3.37	3.21	3.50	3.37
Unit energy cost ($/kVAh)		**0.14**	**0.11**	**0.11**	**0.15**	**0.13**	**0.13**	**0.12**
Excess energy (MVAh)		7213.64	6567.14	6596.18	6754.54	7093.73	6488.57	6735.34

*These values are rounded down to integers. **These values are rounded up to integers.

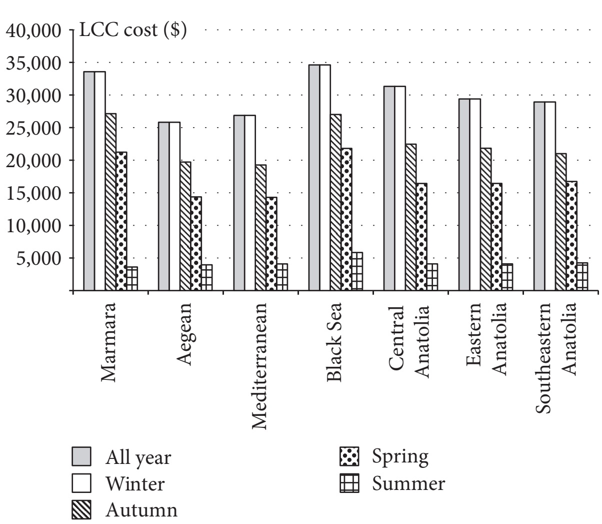

Figure 3: Changes in LCCs by scenarios and geographical regions.

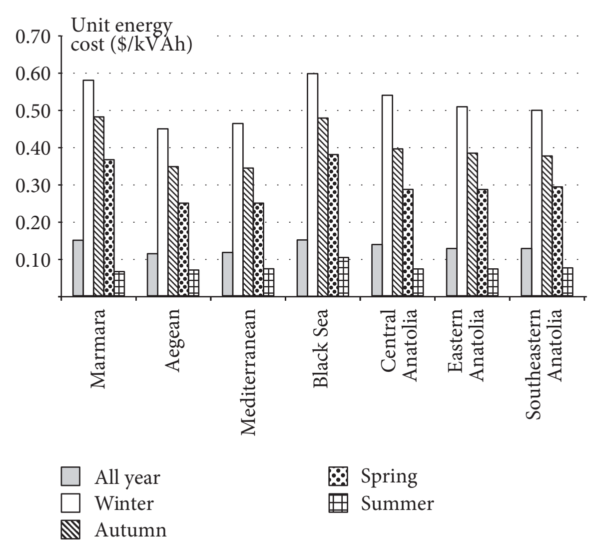

Figure 4: Comparison of unit energy costs by geographical areas and scenarios.

Table 4: Comparison of studies in the literature in terms of UEC.

Ref. number	Authors	Year	Location	System life (years)	Discount rate (%)	Inflation rate (%)	System power (kWp)	UEC ($/kWh)
[19]	Nordin and Rahman	2015	Malaysia	25	6.85	2.8	1.40	0.34
[20]	Chel and Tiwari	2010	India	30	4	n/a	2.32	0.96 (0.8 €/kWh)
[21]	Roy and Kabir	2011	Bangladesh	20	10	n/a	0.4	1.046
							14	0.582
[22]	Ghafoor and A. Munir	2014	Pakistan	20	8	4	2	0.15
[23]	Kamalapur and Udaykumar	2010	India	25	n/a	n/a	0.14	0.258
[24]	Hassan et al.	2016	Iraq	20	9	3	3.1	0.51
[6]	Al-Karaghouli and Kazmerski	2009	Iraq	30	6	n/a	6	0.444
Used model in this article		2017	Turkey	25	18	12	1	0.11~0.15 (all-year sce.) 0.24~0.37 (spring sce.) 0.06~0.10 (summer sce.) 0.33~0.46 (autumn sce.) 0.45~0.60 (winter sce.)

discount rates in the country. Discount and inflation rates are taken as 18% and 12%, respectively, considering the general average of Turkey. The effect of changes in these rates on the UEC and LCC could be a different study. As shown in Figure 4, the winter is the most disadvantageous scenario in terms of UEC. For all scenarios, the most disadvantaged region is also the Black Sea. The difference between the highest (Black Sea, 0.60 $/kVAh) and the lowest (Aegean, 0.45 $/kVAh) UEC values in the winter scenario is around 25%. The summer scenario has the lowest UEC values. UECs in this scenario are less than $0.1. Differences between geographical regions are also relatively reduced. For this reason, the correct determination of operation time interval in SAPV system design is very important in terms of UEC. Excluding the summer scenario, the most favorable time intervals are all-year, spring, and autumn seasons.

In this study, classical analytical calculation method is used. Similar methods are used for both technical and economic analyzes in many studies. In LCC and UEC calculations, in particular, the economic conditions of the country, the assumptions made, and the system life are important parameters. In addition, the unit costs of SAPV system components have been decreasing over the years. Besides, the incentives and subsidies given by the governments of the countries also show significant changes. In [19], the authors calculated 0.34 $/kWh UEC for a 25-year lifetime, 2.8% inflation, and 6.85% discount rate assumptions for a SAPV system to be established in Malaysia. Chel and Tiwari conducted analytical technical and economic analysis for a SAPV system in New Delhi, India. In that study, the system life is 30 years and the interest rate is 4%. In the LCC analysis made with these assumptions, UEC was calculated as 0.80 €/kWh (0.96 $/kWh) [20]. Considering that the study was published in 2011 and the battery replacement period was considered as 5 years, it can be explained that the results are considerably higher than the results obtained in this article. Roy and Kabir have made UEC comparisons for oil, diesel, and SAPV power plants. For the 10% discount rate (inflation rate is neglected), the UEC value has changed from 1.046 $/kWh (for 0.4 kWh daily demand) to 0.582 $/kWh (for 14 kWh daily demand) [21]. Ghafoor and Munir performed SAPV system design at about 2 kWp for a domestic user in Faisalabad, Pakistan. In this study, inflation and discount rates were taken as 4% and 8%, respectively. UEC was estimated at about 0.15 $/kWh (14.8 PKR/kWh) [22]. Kamalapur and Udaykumar also considered government subsidies in the LCC analysis of the small powerful SAPV system. However, in this study, the interest and inflation rates in the country have been neglected. The system life was assumed to be 25 years, and the UEC without subsidy was calculated as 0.258 $/kWh (14.11 Rs/kWh). Considering the subsidies, the unit cost was 0.145 $/kWh (7.91 RS/kWh) [23]. Table 4 gives comparative results of the abovementioned literature examples with this study.

3.3. Capacity Utilization Rate Calculations. The CUR is related to the amount of excess energy produced. Since the load demand is a key element in determining all parameters of the system, SAPV plants usually have excessive energy. Therefore, the rate of electrical capacity utilization is always below 100%. As can be seen from Figure 5, the changes in CURs show differences, especially in seasonal use. In the all-year scenario, it is below 4% for all regions. However, it is over 23% in winter and summer scenarios. It was calculated that all-year and winter scenarios give parallel results in LCC values. However, the time intervals with the highest

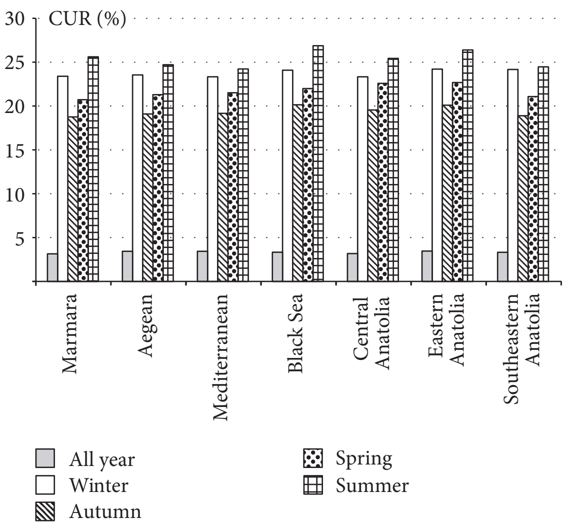

Figure 5: Changes in electrical capacity utilization rates.

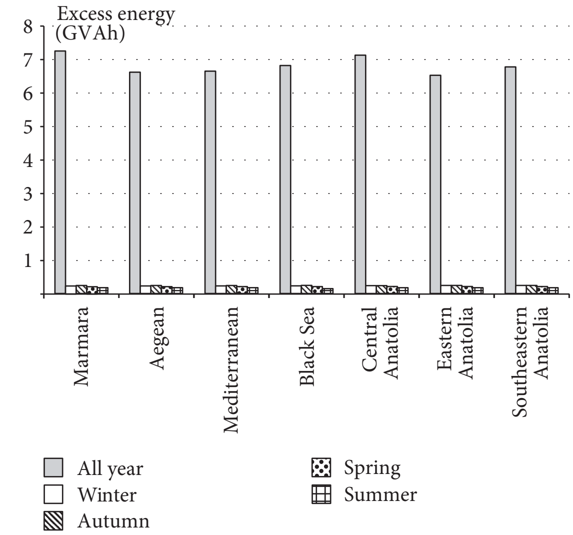

Figure 6: Excess energy produced by PV array.

CURs are designated as summer and winter scenarios. Because during these periods, the values of sun hours between days change less than other scenarios. This means that the amount of excess energy that comes out of the sizing done by taking the worst month value is lower than in the other seasonal periods. The highest and lowest CURs for the winter scenario were calculated for the Eastern Anatolia (24.15%) and the Central Anatolia (23.28%) regions, respectively. In the summer scenario, the highest rate was determined for the Black Sea (26.77%) and the lowest rate was obtained for the Mediterranean (24.19%) regions. The highest CUR for the spring scenario was in the Eastern Anatolia region (22.63%). It is noted that CURs do not generally make a significant difference between regions.

3.4. Effect Analysis of Excess Energy Usage. The excess energy produced varies inversely with the CURs. The values forming the graphs in Figure 6 are calculated by subtracting the energy value that the load will consume for 25 years from the energy values to be produced by SAPV according to the selected scenario. Especially in the all-year scenario, excess energy amount is very high. Marmara region was the most disadvantaged geographical region in this respect. An energy surplus of 7.21 GVAh was generated in this region. In the other six regions, these values range from 6.7 GVAh to 7.1 GVAh. Therefore, geographical regions show similar features in terms of this parameter. In the entire seasonal scenarios, the excess energy is 0.25 GVAh or less. All calculation results for LCC, UEC, CUR, and excess energy are summarized in Table 5.

The sale or use of excess-generated energy is generally not within the scope of this article. However, the use of excess energy in the all-year scenario will have a significant impact on the UEC of the system. According to the results, the energy consumed by the load was about 3% of the total energy production. For this reason, the effect of the excess energy usage on the UEC for the all-year scenario was taken into account. As shown in Figure 7, the UEC average of 0.127 \$/kVAh when no excess energy is used decreases to about 0.06 \$/kVAh and about half when 5% of this energy is consumed with additional loads. For this reason, especially seasonal design of load values in SAPV systems can provide significant efficiency.

4. Conclusions

In this study, a SAPV system design algorithm was developed using a classical analytical method. Using the monthly average sun hours for 75 different locations of Turkey, the technoeconomic analysis of the SAPV system was realized for each geographical region. The developed algorithm groups the calculation results for each location according to the geographical regions of Turkey. In addition, the requested data is output graphically. The SAPV system components have been resized for five different operating period scenarios with a 1000 VA load. The numbers of module, battery, and charge regulator to be used were calculated. Depending on the selected components, BOS, O&M, and replacement costs were also calculated separately. The effects of LCC, UEC, CUR, and excess energy usage rates discussed in detail in the previous section were also examined.

The conclusions obtained can be briefly summarized as follows:

(1) There are no significant differences between the geographical regions of Turkey in terms of LCC and UEC. Therefore, all locations of the country are suitable for SAPV installation with appropriate designs. However, especially the Mediterranean, Aegean, and Eastern Anatolian regions are the most advantageous geographical regions.

(2) In 2017, energy sales price (ESP) for residential consumers of Turkey is given as 42 krş/kWh (0.42 TL/kWh) including funds and taxes [25]. This value corresponds to approximately 0.12 \$/kWh (\$1 = 3.5 TL). When the UEC averages are compared with the current electricity energy tariff

Table 5: Calculation results for all scenarios.

Scenario	Parameter	Geographic regions: Marmara	Aegean	Mediterranean	Black Sea	Central Anatolia	Eastern Anatolia	Southeastern Anatolia
All-year	LCC ($)	33,767.81	26,148.64	26,983.87	34,790.57	31,506.77	29,520.64	29,070.78
	CUR (%)	3.16	3.46	3.44	3.37	3.21	3.50	3.37
	UEC ($/kVAh)	0.14	0.11	0.11	0.15	0.13	0.13	0.12
	Excess energy (MVAh)	7213.64	6567.14	6596.18	6754.54	7093.73	6488.57	6735.34
Spring	LCC ($)	21,089.43	14,465.38	14,360.8	21,883.58	16,600.55	16,525.18	16,929.11
	CUR (%)	20.69	21.23	21.45	22.02	22.53	22.63	21.07
	UEC ($/kVAh)	0.35	0.24	0.24	0.37	0.28	0.28	0.29
	Excess energy (MVAh)	227.3	219.94	217.17	209.91	203.88	202.67	222.11
Summer	LCC ($)	3806.91	4097.85	4150.13	5899.96	4274.67	4291.10	4462.92
	CUR (%)	25.54	24.66	24.19	26.77	25.28	26.38	24.41
	UEC ($/kVAh)	0.06	0.07	0.07	0.10	0.07	0.07	0.08
	Excess energy (MVAh)	172.90	181.17	185.84	162.20	175.27	165.47	183.61
Autumn	LCC ($)	27,231.44	19,940.98	19,419.5	27,113.18	22,594.28	21,907.86	21,228.19
	CUR (%)	18.76	19.05	19.10	19.99	19.50	20.08	18.89
	UEC ($/kVAh)	0.46	0.34	0.33	0.46	0.39	0.37	0.36
	Excess energy (MVAh)	253.99	249.25	248.42	234.67	242.05	233.39	251.80
Winter	LCC ($)	33,767.81	26,148,64	26,983.87	34,790.57234.67	31,506.77	29,588.47	29,070.78
	CUR (%)	23.30	23.37	23.32	24.03	23.28	24.15	24.12
	UEC ($/kVAh)	0.58	0.45	0.46	0.60	0.54	0.51	0.50
	Excess energy (MVAh)	190.89	190.14	190.39	183.39	191.11	182.12	182.47

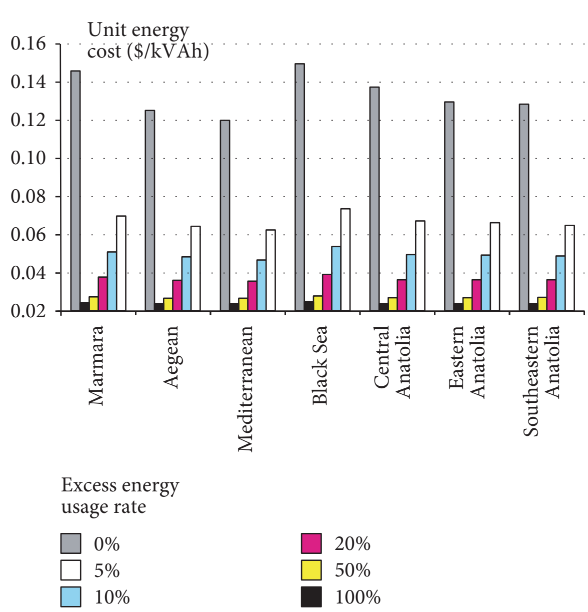

Figure 7: Effect of using excess energy on UEC in the all-year scenario.

(i) the average UEC for winter scenario is 43.3 times higher than ESP;

(ii) for the autumn scenario, this value is calculated as 32.3 times of ESP;

(iii) the cost of energy for the spring scenario is about 24.4 times higher than ESP;

(iv) the all-year scenario is the second most advantageous time period and this value is calculated as 10.6 times of ESP;

(v) in the summer scenario, UEC is highly competitive. It is only 6.2 times more than the ESP.

(3) It can be said that LCC and UEC have become more advantageous at seasonal loads. Especially in the summer, these values are declining significantly at 87% compared to the winter scenario. Therefore, it is very important to correctly determine the operation period of the load of SAPV system.

(4) The operating period of the load also affects the components that make up the LCC. In SAPV systems, approximately 80% of LCC consists of

storage and PV array components. However, in seasonal scenarios, the share of these components varies considerably.

(5) UECs in SAPV systems are considerably higher than in conventional systems. However, the environmental and economic benefits provided by these systems are also very critical for sustainable development. For this reason, many countries are taking measures to encourage SAPV investments. In this study, analyses made in different countries and dates are also compared in terms of UEC. UEC values vary depending on parameters such as economic conditions of the countries, discount, and inflation rates.

(6) Capacity utilization rates also vary significantly between scenarios. This value can be increased by selling SAPV-generated energy or by feeding seasonally additional loads. Thus, UEC can also be reduced.

(7) In this study, comparison was made in terms of the geographical regions of the country. Therefore, constant parameters such as inverter and salvage cost to be added to the system will not significantly change the results to be obtained above.

(8) The developed algorithm can be modified in the following studies to add options such as selling the excess energy to the national grid. Thus, the advantages of legal regulations allowing residential consumers to sell energy can be demonstrated.

(9) The proposed model can be used for any location depending on the meteorological data. In addition, it can realize economic parameter sensitivity analyses (e.g., different discounts, inflation rates, and government subsidies). Comparisons of LCCs for different brands and models of SAPV system components can also be performed with the exception of outputs from this study.

Nomenclature

$\sum L$: Daily load demand (Ah/day)
S_L: Load rated power (VA)
n_{hour}: Yearly operating hour's number
n_{day}: Yearly operating day's number
V_b: Battery voltage (V)
η_w: Wiring efficiency
η_b: Battery efficiency
n_{SD}: Number of storage days
T_{min}: Peak sun hours
$\sum C_B$: Total battery capacity (Ah)
D_T: Temperature effect on battery correction factor
D_{ch}: Charge-discharge correction factor of the battery
(disch): Percentage of battery discharge rate
C_B: Unit battery capacity (Ah)
n_b: Number of batteries
I_{PV}: Total current drawn from PV array (A)
n_M: Number of PV modules
I_M: The current of the selected module (A)
P_R: Present worth factor
i: Inflation rate
d: Discount rate
n: System life cycle
$P_{Worth,n}$: The present worth of the cost for any "n" year ($)
C_0: Initial investment cost ($)
$\sum P_{Worth}$: Total present worth ($)
LCC: Life-cycle cost ($)
$\sum C_0$: Total initial investment cost ($)
$C_{O\&M_{PWorth}}$: Present worth of O&M costs ($)
$C_{R_{PWorth}}$: Present worth of replacement costs ($)
W_{PV}: Daily energy production of PV array (Ah/day)
W_{LC}: Total energy production (kVAh)
W_L: Total energy demand (kVAh)
CUR: Electrical capacity usage rate
UEC: Unit energy cost ($/kVAh)
ESP: Energy sales price ($/kWh, TL/kWh).

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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