OPTIMIZATION OF PHOTOVOLTAIC SYSTEM AND TECHNOLOGY IN VIEW OF A LOAD PROFILE
Case of Public Building in Turkey

by

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The optimum sizing of photovoltaic technologies depends on certain variables such as the daily energy consumption of buildings and available solar potential of the location. The purpose of this paper is to define the optimum photovoltaic panel area with no battery system to supply the daytime electricity usage of a Vocational School in Sanlıurfa, Turkey. First, the maximum photovoltaic panel areas are found at the 100% self-consumption for the Mono-Si, Multi-Si, and CdTe photovoltaic technologies. Besides, for defining optimum installation powers, an economic analysis has been carried out. The seasonal performances of economical optimum capacities are investigated under the feed-in tariff scenario.

At 100% self-consumption, the maximum photovoltaic panel areas are found 130 m^2, 160 m^2, and 170 m^2 for Mono-Si, Multi-Si and CdTe respectively. The results show that the installation of Mono-Si (115 m^2), Multi-Si (150 m^2), and CdTe (210 m^2) photovoltaic systems at 1.65, 1.75, and 2.3 times as the daily peak electricity consumption, is the most optimal selection according to economic indicators.

Key words: *photovoltaic generation, self-sufficiency, life-cycle savings, load profile, optimal installation power*

Introduction

Photovoltaic (PV) cells are semiconducting materials that directly convert the sunlight coming to their surfaces into electrical energy. Depending on PV technology, the solar energy can be converted to electric energy with efficiency between 9% (Organic) and 25% (Crystalline) [1]. Mono-Crystalline (Mono-Si), Multicrystalline (Multi-Si), and Thin-film Silicon are the most widely used PV technologies with the highest market share. Mono-Si technology is the most efficient of all PV technologies. Although Multi-Si technology is less efficient than Mono-Si, it is considered to be the leader of PV technology [2]. The PV systems are used in every field where electricity is needed. Depending on the application, PV systems are built up using accumulators, inverters, battery chargers and various electronic backup circuits. The PV systems were previously used in residential areas without electrical grid. Today, these systems have become widespread in grid connection, in large areas and in the roofs of houses. In particular, PV systems have become one of the renewable energy systems that have been integrated into buildings, making it possible to attain zero (low) energy

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consumption buildings. Environment-friendly PV systems have been reported to offer more economical solutions than conventional systems. For example, a recent study [3] reported that establishing a solar PV system is 30% cheaper than Diesel generators currently in use for residential buildings in Nigeria.

In addition to PV technology, meteorological and geographical conditions also affect the electricity generation performance of PV systems. There are previous studies on generated energy, cost analysis, annual income and required installation areas of PV systems in different technologies for particular region. This study [4] aims to analyze three different type PV panels (Mono-Si, Multi-Si, Thin-film) to determine optimal panel for Kahramanmaraş in Turkey. These PV systems are 3 kWp, separate and grid-connected. Cost analysis of each system was used to determine the most optimal panel type. The system consisting of Multi-Si type PV is the most suitable for the region, because it has the highest annual incomes and the shortest breakeven point. In addition, the rooftop solar PV potential of an entire city is also investigated. A study [5] applied Hillshade analysis to estimate the available rooftop area of Gangnam district in Seoul, South Korea. The total solar radiation on the rooftop (9287982 MWh), the available rooftop area (4964118 m^2) and the electricity generation (1130371 MWh) were found. A similar study [6] calculated solar energy potential in Andalusia for grid-connected PV systems installed on residential rooftops. For this purpose, statistical construction data and digital urban maps were used to measure the useful the roof surface area. In conclusion, the study reports that if PV arrays were installed on all of residential building rooftops of Andalusia, this would satisfy 78.89% of all energy needs. Another study [7] identified the economic feasibility of the Multi-Si PV systems in commercial buildings for three locations in Baja, California, Mexico. The energy generation of PV technologies was estimated on TRNSYS. The performance of locations were compared with respect to economic indicators such as return on investment period and cost-benefit factor.

Finding the optimum size and location of PV systems has become a top priority for researchers. A study [8] proposes a framework to integrate geographical information system, mathematical optimization and simulation modules to obtain the optimal size of the PV units and the optimal location in a campus area. In another study [9], the optimization results of a market in Germany were given in terms of self-consumption and self-sufficiency. Optimization was performed using real load profile and solar radiation data. Techno-economic and sensitivity analyses were applied to show the effects of PV systems costs and interest rates on PV system size. The results show that systems with PV peak power up to twice as the peak load are the most economical scenarios. A similar study [10] aimed to improve the self-sufficiency ratio of PV electricity in order to reduce electricity consumption from grid in commercial buildings at 100% self-consumption without any battery storage. The analysis based on the selection of the external surfaces of the building that get the best fit of the PV generation profile in accordance with building's load shape. The most favorable PV orientation was found in South and Southeast direction and the highest average self sufficiency was 41% in the case study for a building in Madrid, Spain.

The optimum energy control of a grid-interactive solar PV system is also investigated in previous studies. The effect of grid electricity prices and battery-storage on grid-interactive 3 kW residential PV system has been examined [11] for the case of eThekwini municipality in South Africa. The results show that the use of battery storage system is only beneficial to the system when the feed-in tariff (FIT) is not attractive. The results also show that higher the grid electricity price, the higher the profitability of the PV system. In another case, the optimum size of grid-connected PV system is investigated in terms of household use in Austria [12]. The results showed that regulations encourage very small PV systems (<5kW). Small systems are often more expensive and have led to increase in PV total cost in the residential sector. Another study [13] presented a simulation model to identify most profitable PV system size and storage for residential usage. Germany and Ireland are compared to explore what drives the profitability of self-consumption and self-sufficiency in different countries. For the most profitable combinations for PV and storage system sizes, self-sufficiency rates of 75% and 65% were reached for Germany and Ireland, respectively. The results show that increasing self-sufficiencies beyond these levels will decrease the profitability of PV storage systems significantly.

The load profile (consumption pattern) which is the daily variation of electricity consumption depends on a few parameters such as building type (residential, office *etc.*), season, day of the week. Load profile of the building has an important effect on optimal PV system sizing and cost performance. For accurate PV system sizing analysis, hourly solar radiation data and load profile of the building should be used. From the aforementioned literature review, it can be seen that there are not many studies on optimization of 100% self-consumption on grid PV system with no battery storage. The energy storage has a negative effect on profitability for attractive FIT and increases investment and maintenance costs of PV system for most buildings. Therefore, no battery storage condition was applied in the analysis. Life-cycle savings (LCS) is the difference between the cost of electricity consumption from the grid and the cost of PV system. Although there are many optimization studies, LCS analysis of PV systems is not previously studied. This paper proposes an optimization method of P1, P2 which applies an LCS analysis under FIT that is assumed to be equal to grid electricity price.

Method

In this study, buildings of Vocational School of Technical Sciences in Sanlıurfa were analysed. The campus located in Sanlıurfa, Turkey is at 37.70 N and 38.49 E and the satellite image is shown in fig. 1.

Figure 1. Roof surfaces of Vocational School of Technical Sciences that can be used for the electricity generation by PV system

In order to meet the electricity demand of the school, PV system is designed to be installed on the roof surface of the buildings. It is assumed to be an on grid system that excess generated power can be sent to the grid. The PV technologies are selected from the commonly used Mono-Si, Multi-Si, and CdTe.

The total roof area of school is 4564 m^2 and the average slope of the roofs is 10º. It is assumed that roofs with azimuth angles between 67.50° (northwest) and –67.50° (northeast) are not suitable for PV installation. The azimuth angles of available roof surfaces are found as γ = 52° (southwest) and γ = –52° (southeast). So, the available roof space for the installation of PV panels is calculated to be 2020 m^2.

In this study, total solar horizontal radiation, *I,* values of Sanlıurfa are obtained from meteorological data for 2014 and 2016. The average of ten-minute measured data is assumed to be constant over that one hour period. Total solar radiation values on the inclined surface is calculated by the isotropic diffuse model given in the reference [14]. With this method, the total solar radiation is calculated:

$$I_T = I_b R_b + I_d \left(\frac{1+cos\beta}{2} \right) + I\rho_g \left(\frac{1-cos\beta}{2} \right) \tag{1}$$

The expressions on the right side of eq. (1) are the direct, diffuse and reflected elements of the total solar radiation, respectively. The I_b and I_d values show total direct and diffuse radiation on the horizontal surface. The β is the surface slope angle. The geometric factor, R_b, is calculated:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{2}$$

The angle of incidence, θ, is the angle between radiation on a surface and normal to that surface. The relation between the surface angle of the radiation and other angles is expressed [14]:

$$\begin{aligned}\cos(\theta) = {} & \sin(\delta)\sin(\varphi)\cos(\beta) - \sin(\delta)\cos(\varphi)\sin(\beta)\cos(\gamma) + \\ & + \cos(\delta)\cos(\varphi)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\varphi)\sin(\beta)\cos(\gamma)\cos(\omega) + \\ & + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)\end{aligned} \tag{3}$$

For horizontal surfaces, the angle of incidence is equal to the zenith angle, θ_z. In this case, the slope angle $\beta = 0$ and the equation becomes as the expression:

$$\cos(\theta_z) = \cos(\varphi)\cos(\delta)\cos(\omega) + \sin\varphi\sin(\delta) \tag{4}$$

The φ is the local latitude angle, ω – the hour angle, γ – the azimuth angle and the value on south facing surfaces is zero. The declination angle δ is calculated:

$$\delta = 23.45 \sin\left[\frac{360(284+n)}{365} \right] \tag{5}$$

The general formula for determining the electricity generated as output of a PV system is [15]:

$$E = A_c \eta I_T Pr \tag{6}$$

where A and η is the total panel area and the panel efficiency, *Pr* is the performance ratio including all losses and its value is assumed as 0.75.

In this study, the P_1 P_2 method [14] which is known as LCS method, is used to determine the optimum installed capacity of PV systems according to economic indicators. The LCS is calculated:

$$LCS = P_1 C_F \, L F - P_2 \left(C_A A_c + C_E \right) \tag{7}$$

The C_F is the unit cost of electricity and *L* is annual electricity consumption. The A_c represents PV panel area. The C_A and C_E represent area-dependent costs and costs which are independent of PV area, respectively. In this study, C_F is 0.087 euro/kWh and C_E is neglected. For the determination of C_A, the efficiencies of PV Panels; Mono-Si, Multi-Si, and CdTe were taken as 24.4%, 19.9%, and 18.6%, respectively [1]. In case of using Mono-Si technology, it is assumed that 4.1 m^2 of PV surface area is required for 1 kWp PV capacity. 5 m^2 of Multi-Si and 5.4 m^2 of CdTe PV surface area is required for 1 kWp PV capacity. The installation costs of Mono-Si, Multi-Si, and CdTe technologies were assumed as 1.35, 1.32, and 1.29 €/Wp, respectively [16]. Where the self-sufficiency, F, is the ratio of PV electricity consumption, E_C, to the electricity demand of school, E_L,. The F is calculated:

$$F = \frac{E_C}{E_L} \tag{8}$$

In this study, electricity consumption values of school were used for 3 years between 2015-2017.

The P_1, given in eq. (7), is the ratio of life-cycle electricity cost savings to first-year electricity cost savings and calculated:

$$P_1 = \left(1 - C\overline{t}\right) PWF\left(N_e, i_F, d\right) \tag{9}$$

where C indicates income producing or non-income producing (1 or 0, respectively), i_F – the electricity inflation rate, and d – the discount rate. In this study i_F and d were assumed as 0.8 and 0.9 according to 2017 economic data, respectively. The N_e is the period of economic analysis and assumed to be 25 years. The P_2 is the ratio of life-cycle expenditures to initial investment and calculated:

$$P_2 = 1 + M_s P_1 + \frac{R_v}{\left(1 + d\right)^{N_e}} \tag{10}$$

where M_s is the ratio of first-year miscellaneous costs to initial investment and R_v – the ratio of resale value at the end of period of analysis to initial investment. In this study M_s and R_v were assumed as 0.01 and 0.4, respectively.

The C_S is the initial investment cost and the payback period, N_p, is calculated:

$$N_p = \frac{\ln\left[\dfrac{C_S\left(i_F - d\right)}{FLC_F} + 1\right]}{\ln\left(\dfrac{1 + i_F}{1 + d}\right)} \tag{11}$$

Self-consumption, G, is the ratio of PV electricity consumption, E_C to electricity generated from PV panels, E_{PV} and calculated:

$$G = \frac{E_C}{E_{\mathrm{PV}}} \tag{12}$$

The cost of generation of electricity from PV panels, $C_{E_{PV}}$, is calculated:

$$C_{E_{PV}} = \frac{C_S}{N_e FL} \tag{13}$$

Results and discussion

The electricity demand calculated according to average data for four seasons is shown in fig. 2. As seen from figure, the highest daily total energy consumption is 436 kWh in winter and reaches 23 kW at peak demand. In summer, this values drops to 278.5 kWh and the yearly average of daily total electricity consumption is 334 kWh. Peak electricity demand of the school is 17 kW according to yearly average.

Electricity generation with PV panel

Figure 2 shows the variation of generated electricity in a unit area of Mono-Si, Multi-Si, and CdTe PV panels during the day. The hourly average solar radiation data is used for calculation of PV generated electricity. A total electricity output of 0.94 kW/m^2, 0.77 kW/m^2, and 0.72 kW/m^2 can be obtained for Mono-Si, Multi-Si, and CdTe during a yearly mean day.

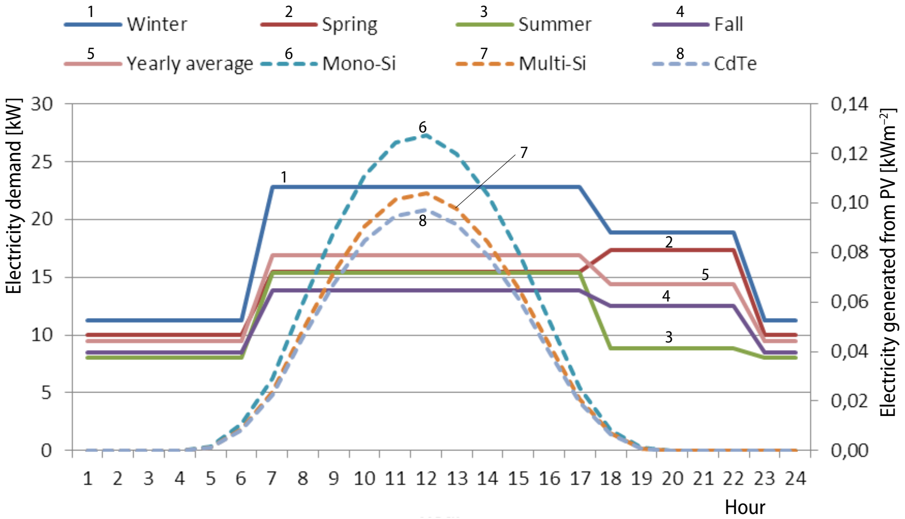

Figure 2. Hourly variation of the seasonal electricity consumption and the electricity generation per unit area of three different PV technologies

The variations of the self-sufficiency and self-consumption of the three different PV technologies with panel area are shown in fig. 3. This graph is shaped by the average daily peak electricity demand of 17 kW. For example, in the case of the use of CdTe (assuming 1 kWp PV panel needs 5.4 m^2 surface area) for PV installation, it is possible to reach about 400 kW installed PV on roof of the campus. However, according to the electricity demand of the campus, the optimum capacity of PV installation must be determined.

Selecting maximum PV panel areas according to 100% self-consumption criteria

As can be seen from fig. 3, self-sufficiency increases with the increase of PV panel area. While the annual electricity demand of the campus is constant, self-consumption decreases as the installed PV panel area increases. For all three PV technologies, 37% of the required electricity is provided in the case of complete use of the generated electricity (100% self-consumption). In other words, the self-sufficiency value is 37%. Thus, the maximum PV surface areas (and installed of PV capacities) are 130 m^2 (32 kWp), 160 m^2 (32 kWp), and 170 m^2 (34 kWp) for Mono-Si, Multi-Si, and CdTe, respectively. These values show that installed capacity of the PV system is up to about twice as the yearly average of hourly peak electricity demand (17 kW) at 100% self-consumption. After this point, there is a rapid decline in self-con-

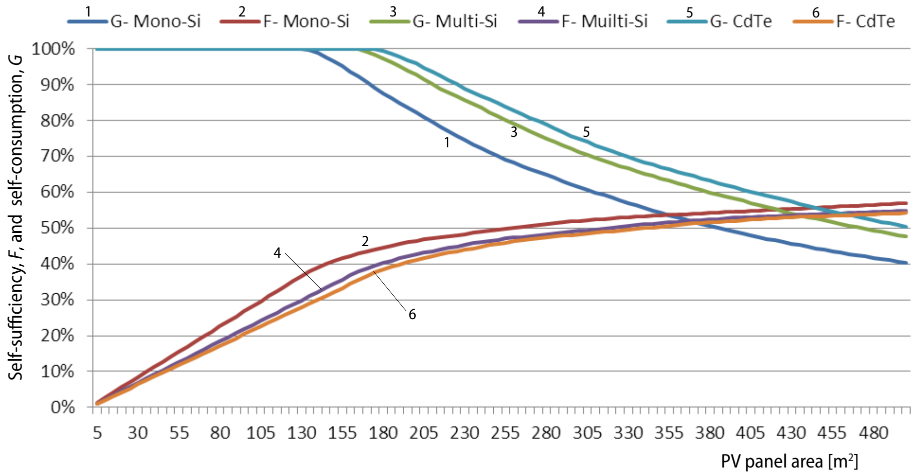

Figure 3. Self-sufficiency and self-consumption for three different PV technologies as a function of panel area

sumption and the slope of self-sufficiency curve decreases to about one-fifth for Mono-Si and one-fourth for CdTe and Multi-Si.

Economic optimization of PV panel area

Figure 4 shows LCS values for three different PV technologies as a function of panel area. At the optimum value, the derivative of the LCS, eq. (7), with respect to PV panel area is zero:

$$\frac{\partial LCS}{\partial A_c} = 0 = P_1 C_F L \frac{\partial F}{\partial A_c} - P_2 \left(C_A A_c + C_E \right) \tag{14}$$

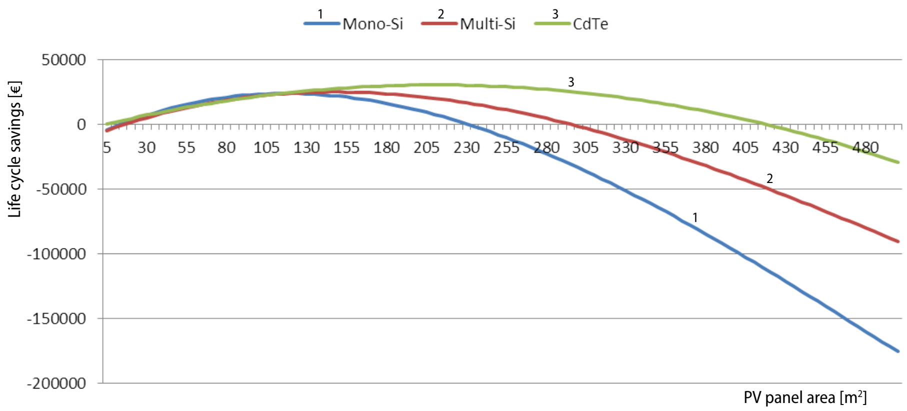

Figure 4. Life cycle savings values for three different PV technologies as a function of panel area

Therefore, the optimum PV panel area is obtained where the slope of the self-sufficiency curve, fig. 3, equals to:

$$\frac{\partial F}{\partial A_c} = \frac{P_2 C_A}{P_1 C_F L} \tag{15}$$

If Mono-Si and Multi-Si PV technologies are used, the optimum panel areas are calculated as 115 m^2 and 150 m^2, respectively. The optimum PV panel area is found to be 210 m^2 for CdTe.

The seasonal performances of the optimum PV panel areas are shown in fig. 5. The excess electricity that PV system generated fed back to the grid. In this scenario, the FIT is assumed to be same with the purchasing electricity price. The FIT scenario is applied to only the PV capacities calculated as the result of economic analysis. As can be seen from fig. 5, for the Mono-Si, the highest panel efficiency, self-sufficiencies values were lower than other PV technologies. The CdTe has the highest self-sufficiency. The reason for this is shown in fig. 6, where the performances of the economic optimum areas for summer season are given. As can be seen in fig. 6, 115 m^2

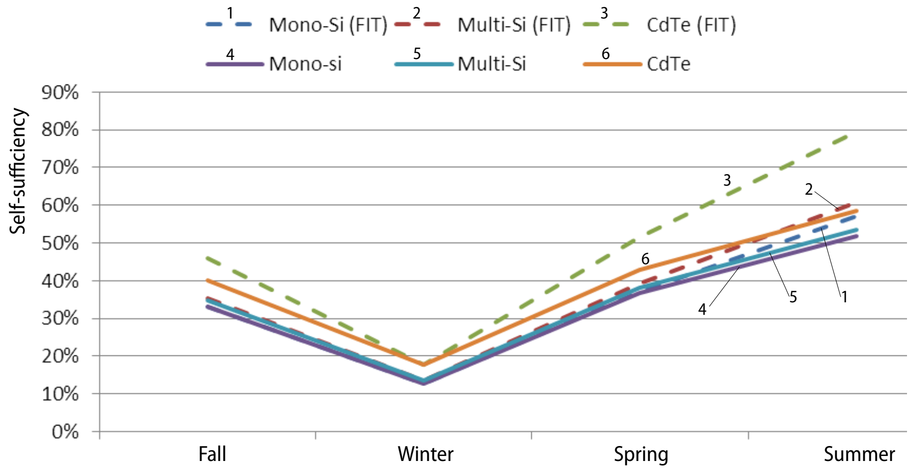

Figure 5. Seasonal performances of optimum PV system capacities of three different PV technologies with FIT scenario

Mono-Si PV panel generates 158.9 kW (E_{PV}) elecricty per day and the school consumes 144.5 kW (E_C). 210 m^2 CdTe PV panel generates 221.2 kW (E_{PV}) elecricty per day and the school consumes 162.9 kW (E_C). Therefore, when CdTe technology is used for school at a constant daily load of 275 kW, the self-sufficiency is higher. Self-sufficiency of Mono-Si is 13% for winter and 52% for summer. The best seasonal performance belongs to CdTe technology and the winter self-sufficiency value is 18% while it is 59% in the summer. In the case of FIT, the self-sufficiency values for summer periods of Mono-Si, Multi-Si, and CdTe technologies were found to be 57%, 61%, and 79%, respectively. The amount of excess electricity is added to consumed electricity, E_C, in calculations and this improves self-sufficiency. For, it can be assumed that excess energy could be stored and used later for the case of FIT. Table 1 shows how the FIT scenario improves seasonal self-sufficiencies. More electricity is generated with CdTe than other technologies, which also helps to maximize self-sufficiency.

Table 1. Relative differences of seasonal self-sufficiency with FIT scenario to self-sufficiency with no FIT scenario for optimum economic areas

	Mono-Si	Multi-Si	CdTe
Fall	0	1.34%	15.20%
Winter	0	0	0
Spring	1.16%	3.56%	20.56%
Summer	9.87%	13.50%	35.72%

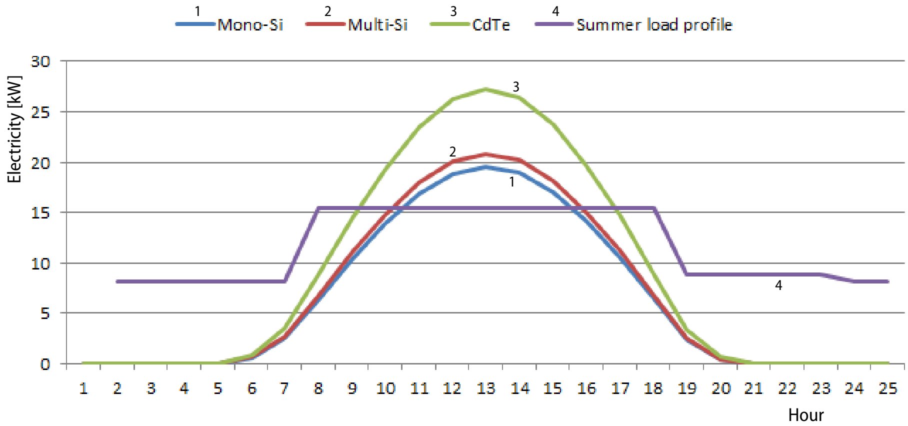

Figure 6. Daily summer performances of PV technologies at optimum economic areas

Table 2 presents economic parameters obtained from the LCS analysis results for PV systems in optimum capacity. As shown in tab. 1, with 42%, CdTe is the technology with the highest yearly self-sufficiency The payback periods of PV technologies are very close to each other and about 12 years. Despite the fact that the initial investment cost of CdTe technology is the highest (50400 €), the LCS for CdTe is found to be 30310 €, and so the highest, as well. For the FIT scenario, the payback period is 11.84 years for CdTe. While the electricity purchase price from the grid is 0.087 €/kWh, the cost of electricity generated by the PV panels is less than half cost (0.038 €/kWh) for three PV technologies.

Table 2. Optimization results of PV systems for three different PV technologies

PV technology	Initial investment [€]	LCS [€]	Payback period [year]	Cost of generated electricity with FIT scenario [€kWh^{-1}]	Optimum panel area [m^2]	Annual electricity generation [kWh]	Optimum self-sufficiency [%]
Mono-Si	37870	23765	12.43	0.0383	115	39535	32
Multi-Si	39450	24874	12.14	0.0375	150	42057	35
CdTe	50400	30310	12.69	0.0366	210	55033	42

Conclusion

In this study, selecting and defining the thermal and economical optimum PV technology without energy storage, has been investigated for a campus area. For this purpose, three most common PV technologies have been compared with parameters such as, LCS, cost of electricity generation, payback period, self-sufficiency and also the advantages in the case of FIT.

At 100% self-consumption, the maximum PV panel areas are found to be 130 m^2, 160 m^2 and 170 m^2 for Mono-Si, Multi-Si, and CdTe, respectively. The most economical capacity that the Mono-Si, Multi-Si, and CdTe PV systems installed is 1.65 (115 m^2), 1.75 (150 m^2), and 2.3 (210 m^2) times as the daily peak electricity demand, respectively. These results show that maximum PV panel areas selected according to 100% self-consumption criteria may not be economical.

The cost of electricity generated by all PV panel types is about 60% cheaper than electricity purchased from the grid.

When optimum self-sufficiency and self consumption values are compared, annual average self-consumption for Mono-Si and Multi-Si is found as 100% and their self-sufficiency is 32% and 35%, respectively. The self-sufficiency value is found to be 42% for the CdTe and average self-consumption is 94%. The yearly average self-sufficiency of CdTe increases to 45% in the case of FIT.

Seasonal self-sufficiencies values of Mono-Si are lower than other PV technologies. With 18% self-sufficiency for winter and 59% for summer, CdTe shows the best seasonal performance among the economic optimum PV areas calculated according to yearly load profile. In case of FIT scenario, the summer self-sufficiency of CdTe technology is 79%.

Nomenclature

A_c – area, [m^2]
C – indicates income producing or non-income producing (1 or 0, respectively)
C_A – area dependent cost, [€m^{-2}]
C_E – costs which are independent of area, [€]
$C_{E_{\mathrm{PV}}}$ – cost of generation of electricity from PV panels, [€kW^{-1}h^{-1}]
C_F – cost of electricity purchased from grid, [€kW^{-1}h^{-1}]
C_S – initial investment cost, [€]
d – discount rate
E – generated electricity, [kWh]
E_C – PV electricity consumption, [kWh]
E_L – electricity demand, [kWh]
E_{PV} – electricity generated from PV, [kWh]
F – self-sufficiency
G – self-consumption
I – hourly solar radiation on a horizontal surface, [Wm^{-2}]
I_b – drect solar radiation on a horizontal surface, [Wm^{-2}]
I_d – diffuse solar radiation on a horizontal surface, [Wm^{-2}]
I_T – total radiation on a tilted surface, [Wm^{-2}]
i_F – electricity inflation rate
L – annual electricity consumption, [kWh]
M_s – ratio of first-year miscellaneous costs to initial investment, [–]
N_e – period of economic analysis, [year]
N_p – payback period, [year]
n – day of the year
P_1 – ratio of the life-cycle electricity cost savings to the first year electricity cost savings, [–]
P_2 – ratio of the life-cycle expenditure to initial investment, [–]
P_r – performance ratio, [–]
PWF – present-worth factor
R_b – geometric factor
R_v – ratio of resale value at the end of period of analysis to initial investment, [–]
$\bar{t}$ – effective income tax rate

Greek symbols

β – slope, [°]
γ – surface azimuth angle, [°]
δ – declination, [°]
η – efficiency, [%]
θ – angle of incidence, [°]
θ_z – zenith angle, [°]
ρ_g – ground reflectance
φ – latitude, [°]
ω – hour angle, [°]

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