Performance comparison of c-Si, mc-Si and a-Si thin film PV by PVsyst simulation

LEVENT YALÇIN[a*], RAMAZAN ÖZTÜRK[b]
[a]*Department of Weather Forecasts, Turkish State Meteorological Service Ankara, Turkey*
[b]*Faculty of Agriculture, Ankara University Diskapi, Ankara, Turkey*

In this paper, electricity demand of a multi-functional agricultural farm is analysed. The farm is located around Ankara and spreaded over 4000 da and installed 400 kW power in electricity. The electricity demand of the farm is simulated by PVsyst in order to comparison the most used three different PV structures for a grid-connected operating type of PV system in the terms of electrical performance indicators. The paper aims to identify the most compatible PV structure for Ankara and its environments. All meteorological and environmental conditions and BOS equipment in three simulations are identical. Many electrical and operating performance indicators are examined in order to compare each other. System efficiency is similar in both c-Si and mc-Si types (~12 %) but the lowest rate in a-Si (5.5 %). As close to system efficiency, special production of the system is the biggest for a-Si, 1689 kWh/kWp/year; second for c-Si, 1607 kWh/kWp/year; the lowest for mc-Si, 1570 kWh/kWp/year. The average per kWp of electricity generation (system yield) is 4.40 kWh/kWp/day for c-Si; 4.30 kWh/kWp/day for mc-Si; 4.63 kWh/kWp/day for a-Si simulations. Although a-Si one's system efficiency is less than others, it is more profitable for Ankara environments. Material and method used in the study is quotation from a doctorate study called "Determination of Solar Energy Potential and Using Possibilities for Research and Application Farm of Agricultural Faculty of Ankara University in Haymana" which is completed in Graduate School of Applied Science of Ankara University in 2010.

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1. Introduction

Electrical Energy Markets and Supply Security Strategy Paper by Turkish Government say that the share of renewable energy sources in electricity generation is planned to be at least 30 % for Year 2023. Although solar energy targets are not specified, it is agreed to "…assessment of the potential of the country to ensure to the maximum extent…", "…following and implementation of technological developments…" and "…strengthening the legal framework to encourage electricity generation…" and announced to the public [1]. Turkish State Meteorological Service (TSMS) and General Directorate of Electrical Power Resources Survey and Development Administration (EIE) studied to identify the potential of solar energy for Turkey in line with efforts to investigate alternative energy sources energy sources which carries on since 1983 all over the world.. The motivation was the oil crisis in 1973. This study gives solar energy potential in the unit of "kcal/cm2-month" due to actinograph devices which measures solar energy not solar power according to the conditions of time (Table 1). Nowadays radiometers like pyranometer measure instant solar power in W/m^2. Duration and intensity of solar radiation of the sun on the basis of geographical regions are also given in Table 2. The Black Sea Region is exposed to the lowest sunshine hours and solar radiation, the South-eastern Anatolia Region has the highest sunshine hours and solar radiation [2].

Table 1. Monthly average solar energy potential of Turkey [2].

Months	Monthly total solar energy		Sunshine duration, hour/month
	$kcal/cm^2$-month	kWh/m^2- month	
January	4.4	51.8	103
February	5.4	63.3	115
March	8.3	96.6	165
April	10.5	122.2	197
May	13.2	153.9	273
June	14.5	168.8	325
July	15.1	175.4	365
August	13.6	158.4	343
September	10.6	123.3	280
October	7.7	89.9	214
November	5.2	60.8	157
December	4.0	46.9	103
Total	112.7	1311.0	2640
Average	308.0 cal/cm^2-day	3.6 kWh/m^2-day	7.2 hour/day

Table 2. Turkey geographical regions, solar energy and sunshine duration.

Regions	Total solar energy, kWh/m^2-year	Sunshine duration, hour/year
South-eastern Anatolia	1460	2993
Mediterranean	1390	2956
Eastern Anatolia	1365	2664
Central Anatolia	1314	2628
Aegean	1304	2738
Marmara	1168	2409
Black Sea	1120	1971

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. PV power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Materials presently used for photovoltaics include mono-crystalline (c-Si), multi-crystalline (mc-Si), amorphous crystalline thin film (a-Si), poly-crystalline silicon (pc-Si), and cadmium telluride (Cd-Te) and copper indium gallium selenite/sulphide (CIGS) [3]. A PV power generation system is classified into three size limits such as small-scale (< 10 kW), medium-scale and large-scale (>1000 kW) [4]. The scale power plant design and sizing detail is important. Small inputs in design stage, which is great for multipliers, the output can result in larger values. Therefore all modules connected to the inverter input arrays must be homogeneous. So the plant should be consisting of same modules which connected in series must have the same number and orientation angles [5].

Because of agricultural farms settle in countrysides instead of urban areas, it is not easy to reach electricity utility in all circumstances. Producing electricity energy needed for agricultural and daily activities in an agricultural farm by itself provide a stand-alone structure against network failure and network interruption. Both increasing of agricultural activities and sun radiation/sunshine duration in the months of spring and summer correspond same period in the year. For this reason agricultural sector suits well to solar energy or photovoltaic (PV) electricity than other sectors.

In the main study that this manuscript quoted, both as technical solar energy potential of Haymana Research and Application Farm of Ankara University (HAVUC) is determined and data set for annual hourly electricity consumption of this farm is generated. Grid-connected type of photovoltaic systems with three different structures of PV modules are simulated to match the electricity consumption of the farm in order to identify what the most compatible PV structure for Ankara and its environs..

2. Material and method

2.1. Material

Research and Practice Farm of Ankara University (HAVUC): There are 4 research and practice farms within Agricultural Faculty of Ankara University. These farms from small to large are Çifteler Fisheries Research and Application Farm with area of 2200 m^2 pool, Kalecik Viticulture Research and Application Farm with area of 8 da, Ayaş Horticultural Crops Research and Application Farm with the area of 150 da and HAVUC with area of 4200 da where is the subject of this study. HAVUC was founded in 1983 around İkizce district which has an altitude of 1060 m located in Sakarya Basin, 42 km to Ankara-Haymana Highway, and 15 km to Gölbaşı district. It is located in the coordinates of 39° 34′ N and 32° 40′ E. The highest and lowest points are 1085 m and 1030 m. Campus facilities are built in the border regions of high elevation. The remaining arable land is used for farming and gardening. As managed harsh continental climate conditions of the land allocated to agriculture, farm and garden are to remain at relatively low elevations. There are no any obstacles that can shadow apart from buildings and trees. It has many facilities such as engine workshop, carpentry, warehouse, irrigation system, pumping, lighting, agricultural processing, social facilities and administration buildings that consume electricity as main energy source. HAVUC has an installed capacity of 400 kW spreaded over those facilities. This suggests that it needs a medium-scale PV power generation system to meet its power demand.

Meteorological data: All of the required meteorological data is gained from weather stations based on observations and mechanical and electronic devices. Two of weather stations by EIE containing temperature, pressure, humidity and solar radiation measurements are at the distance of 15 km and 20 km away from HAVUC. Solar radiation is measured by using pyranometer which are CMP11 model of Kipp&Zonen brand. TSMS employs other three weather stations located in centre of Ankara, Etimesgut district and İkizce district. The long-term measurements and observations which can express climatic characteristics of the region belong to these three stations. Sunshine duration measurements by Campbell-Stokes Heliograph are taken from the station located in centre of Ankara only. According to these data, the annual average temperature is 10 °C for HAVUC. The lowest recorded temperature is -19.0 °C in December; the highest temperature is 38.3 °C in July. Average humidity is almost 82 % in winter time and 63 % in summer time. Annual average cloudiness rate is 3.4/10. The number of days when the sky is completely clear is 4 days/months in winter and 20 days/months in summer. The average annual total precipitation is 400 mm/year in 80 days of year. Average wind speed is 3.0 m/s in whole year.

PV module structure: Mono-crystalline cells are cut from a chunk of silicon that has been grown from a single crystal. These are more efficient in converting the sun's rays to electricity and also more tolerant to heat. A multi-crystalline cell is cut from multifaceted silicon crystal. More surface area is required due to inherent flaws and these panels are less efficient in converting the sun's rays. Also, a 100 watt rated mono-crystalline solar panel and a 100 watt multi-crystalline panel is essentially the same beastie they crank out the amount of electricity. Mono-crystalline cells tend to be uniform in appearance. The multi-crystalline has a shattered glass. Thin film panels are created by the application of a thin layer of silicon or other photovoltaic compounds directly onto various materials. Thin film panels are less efficient than multi-crystalline and mono-crystalline panels, so a larger surface area is required [6]. The high efficiency devices commonly use single crystal silicon grown on crystalline substrates. Some of the substrates used are multi-crystal silicon, SiO_2, graphite, amorphous carbon, AlN, BN, etc. Photovoltaic cells contain light absorbing material in the middle of the cells converting photons into carriers via the photovoltaic effect, different photovoltaic technologies are identified by the composition of this absorbing material. As the carriers are generated, they are separated into electrons and holes and then collected at the contacts [7].

PVsyst Software: PVsyst is a PC software package for the study, sizing and data analysis of complete PV systems. It deals with grid-connected, stand-alone, pumping and DC-grid PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools (Fig. 1). In addition, software tools include the databases management - for Meteo data and PV components - as well as some specific tools useful when dealing with solar energy systems: import of meteo data from several sources, tables and graphs of meteo data or solar geometry parameters, irradiation under a clear day model, PV-array behaviour under partial shadings or module mismatch, optimizing tools for orientation or voltage, etc. [5].

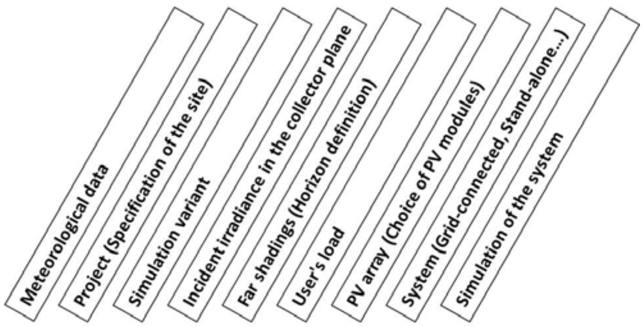

Fig. 1. PVsyst design.

2.2 Method

Design of a PV system: The input information available for the PV designer is usually restricted to the 12 monthly mean values of global horizontal irradiation that characterize the solar climate of the location, and to the electrical characteristics of the PV modules under Standard Test Conditions (STC), as provided by its manufacturers [8]. It is important to decide which parameter must be basis for designing a PV system. Sometimes amount of radiation in a period of time; sometimes energy demand of serving enterprise in power or limits of energy consumption is prior at the beginning of design. Yalcin (2010), suggest a sheet which respectively lists all probable main and sub-elements those must be considered while drawing road map to an ideal PV system (Fig. 2).

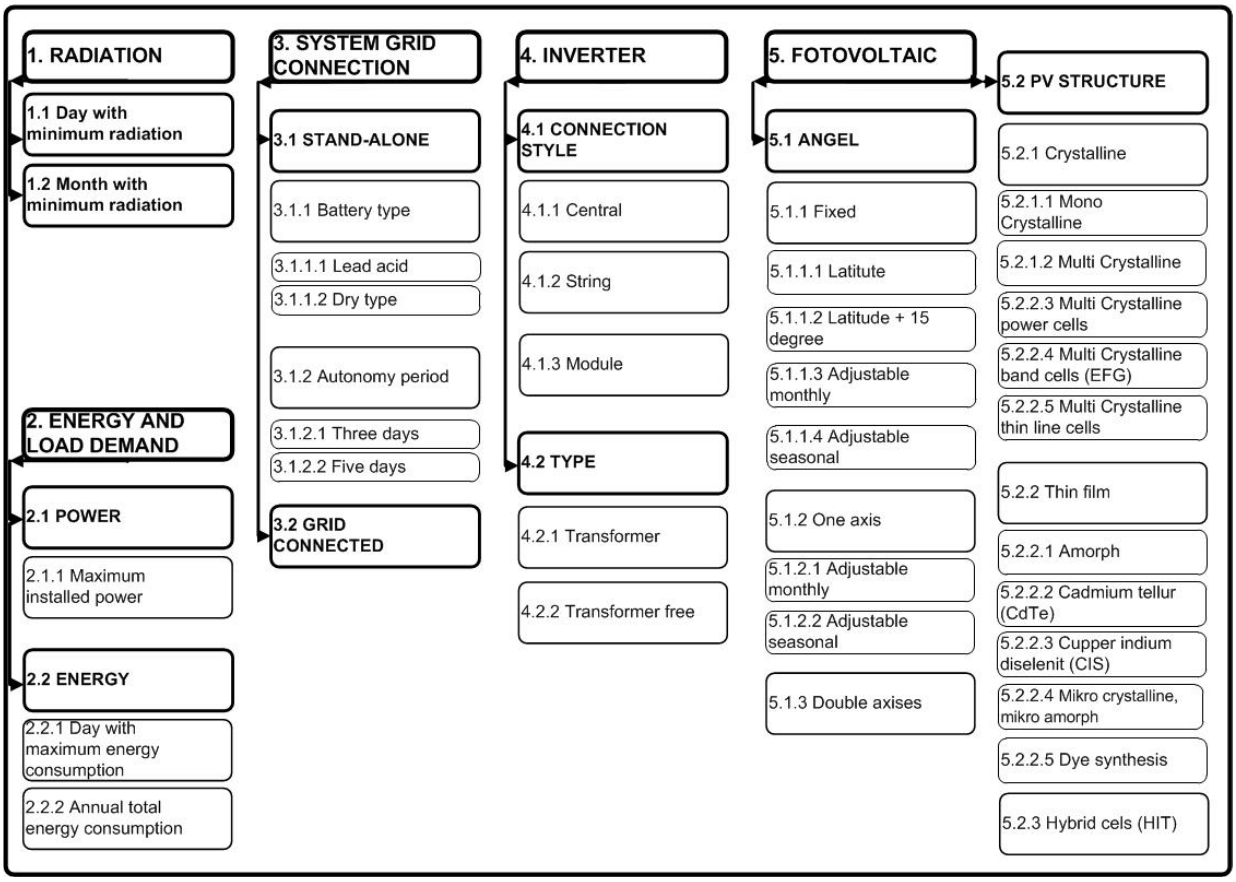

Fig. 2. Work flow diagram for PV system design [9].

It is not easy to reach perfect design of a PV system because of different kind of inputs such as load, radiation, operating style, network connection and component diversity. The electric load and solar radiation are not stable; changing by the time makes it difficult to decide PV system size, type, contents, orientation. Optimum PV panel orientation is calculated by adding 15 degrees to the latitude degree in winter terms in mid-latitudes. 15 degrees must be subtracted from the latitude degree for optimum PV panel orientation if summer terms are used [8]. The vertical orientation of PV panels must be calculated according to the highest production throughout the year for grid-connected PV generating system. FV panel orientation giving the lowest electrical losses and the highest transition factor during the summer period is found 15 degrees by PVsyst optimization tools.

The most important properties of PVsyst are accepting hourly solar radiation and electricity data which are provided from manual measurements. It can simulate draft system designs depending on solar radiation and electricity load in order to present system output data by using algorithms inside. Soto (2004) [10] summarised and compared these algorithms developed by some researchers who studied on energy production predictions models for PV modules. Most known of them are King's model and 5-parameter model. King's model [11, 12, 13] predicts the energy production from a PV array by calculating the current at five strategically located points throughout the current-voltage (I-V) curve. Although the results of the errors obtained for this model are considered to be small, making this its greatest advantage, its disadvantage consists in the large amount of input data that it requires. 5-parameter model done for TRW Inc. by Luft et al. [14] proposed an equation to predict the current produced. This equation is designed to calculate the entire I-V curve, in contrast to King's model, which focuses on only five points such as the maximum power (P_{mp0}), short circuit current (I_{sc0}), open circuit voltage (V_{oc0}), current and voltage at the maximum power point (I_{mp0} and V_{mp0}, respectively), nominal operating cell temperature (NOCT). Electrical values, performances, efficiencies and system losses obtained from PVsyst simulations, are compared with measurements in field conditions, but +/- 5 % is a difference [5].

In this study balance of system (BOS), the PV panel orientation, fixed angle PVs, load factors and solar radiation data are kept the same three types of PV modules (c-Si, mc-Si and a-Si) are compared in a grid-connected PV system. Considering all other conditions are same, which type of three different PV modules is the most compatible to technical and geographical conditions of HAVUC (Ankara) and its environs. Hourly meteorological measurements and hourly electrical consumption data are used in simulations as input data. Hourly (8760 units/year) global solar radiation (W/m^2), temperature (°C) and wind speed (m/s) are given for an entire year and provided to PVsyst software in appropriate format (Fig. 3).

Grid-connected PV system is designed by using PVsyst v5.2 in the permission and support of University of Geneva. In design stage, Fig. 2 (work flow diagram for PV system design) and PVsyst software has leaded designer while deciding which way to be followed and which components to be integrated to the system. Hourly (8760 units/year) electrical energy consumption data in kWh for PV solar power system design is given as an input to the PVsyst software as the load needs to be met (Fig. 4). According to data obtained from energy audit of electrical energy consumption in the winter period, the share of total consumption in the winter period is 34 %; the share of total consumption in the summer period is 66 %. The average daily consumption is 697 kWh/day from October to April (so called winter period) 1210 kWh/day from May to September (so called summer period). Total electric energy consumption of HAVUC Farm is 333 MWh/year and installed electrical power is 400 kW including electrical motors, pumps, lamps, HVAC components.

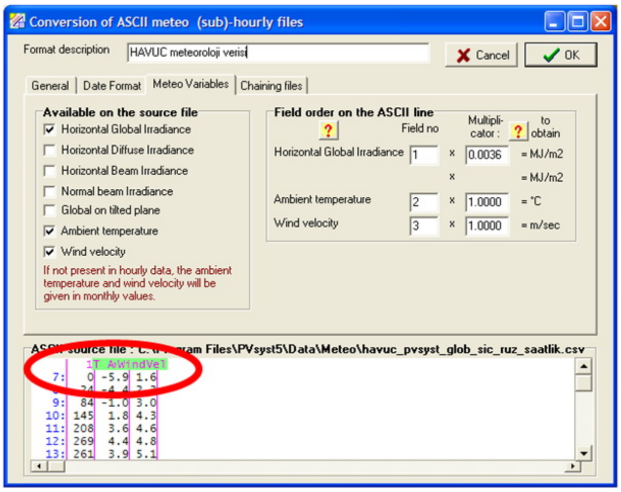

Fig. 3. PVsyst interface for hourly meteorological data input.

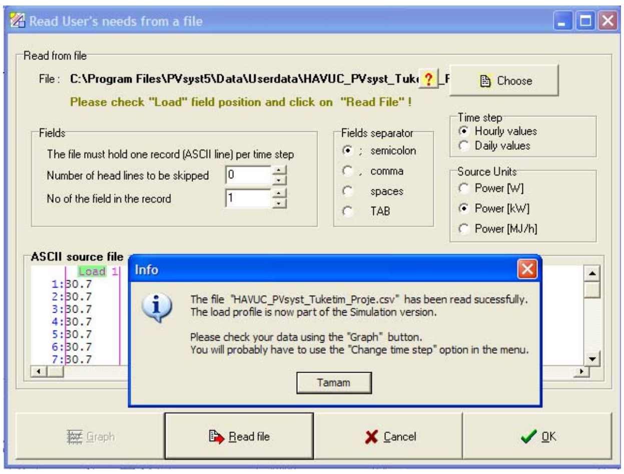

Fig. 4. HAVUC annual hourly electricity consumption data transferred to PVsyst.

The most important criteria in the installation of solar PV electricity production plant is required to meet the load demand. Grid-connected PV plant, because the network can act as back-up power generator, all load demand would be met. In any case, in order to meet the load by means of PV power plant, the calculated potential demand for electric power load should be 25 % more at design and sizing stage. For this reason, electric load of HAVUC Farm is taken 416 MWh/year instead of 333 MWh/year to be used in design and sizing processes. If production is more than the load, PV system gives this excess energy to the grid. Luque and Hegedus (2002) say that grid-connected PV system should be designed as to be able to produce highest electricity throughout the year. However, for the purposes of the study, the PV system is designed by considering distribution of electricity consumption throughout day and year during the year [8].

After deciding operating mode, target season and optimum orientation of PV panels, compatible components should be determined. At this stage, the priority operation sequence is for inverter. One or a group of inverters which has input and output values which can meet the supply and the demand is selected. In this design, a SMA brand central inverter who had capacity of 400 kW, 50-60 Hz, 300-600 V input voltage range is the selected option.

The next step is the selection of PV modules. The PVsyst database contains references to more than 1200 PV modules available on the European market. These earlier data comes from Swiss TISO and German Photon Magazine as well as manufacturer's specifications [5]. In this projection, c-Si Yocasol PCA200 PV module with the power of 200 Wp and the output voltage of 22 V is selected (Fig. 5). Kyocera KC200-GHT2 module with nominal power of 200 Wp for mc-Si simulation and Parabel Uniflat 288 with nominal power of 288 Wp for a-Si simulation are selected in the same way. In all design stages, some of the elements those affect the PV electricity production such as the panel temperature, inclined solar radiation incoming to the panel, effective solar radiation, and the panel electricity production, electricity generation supplied to the network, the panel efficiency and system efficiency are considered (Fig. 6).

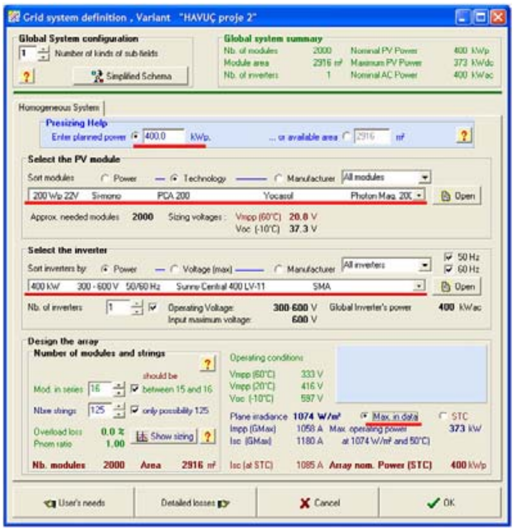

Fig. 5. c-Si PV system components for 400 kW power demand.

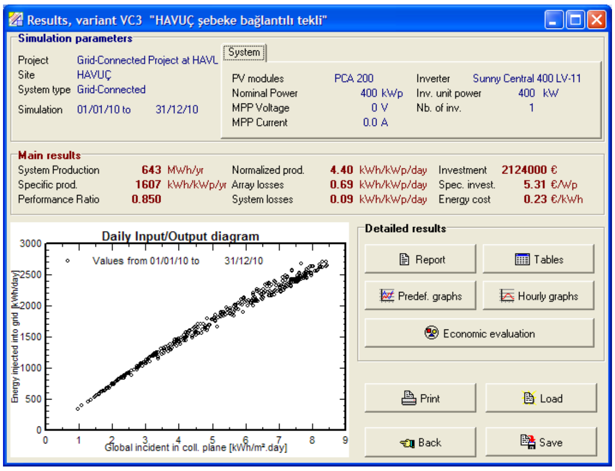

Fig. 6. c-Si PV power generation for 400 kW power and hourly consumption.

After completion of the design, PV module electrical and physical parameters, meteorological inputs measured and calculated, PV system performance ratings and also economical evaluations could be presented side by side for three different PVs (Table 3). Designers or investors can decide which one is more profitable by changing some parameters by size or capacities.

3. Results

Provided that PV panels are oriented in a fixed angle, load demand depending on summer electricity consumption, and BOS components being equal; simulations from three different structures (c-Si, mc-Si and a-Si) are run and compared. Table 3 summaries PV module features, Design parameters, PV system electrical and behavioural features, Inverter input values and Main results containing financial analysis:

1. c-Si and mc-Si PV modules 200 Wp, a-Si PV modules are 288 Wp of power. PV panel angles are 15 degree; Azimuth angle is 0, so PV panels face to south directly; Albedo is accepted 0.33; one central inverter is used for all of three structures.

2. Some design parameters annual means detail such as Wind velocity is 3.0 m/s, Ambient temperature is 10.6 °C, Horizontal global irradiation 1743 kWh/m^2, Incident global irradiation is 1891 kWh/m^2, and Transposition factor is 1.085 (all these parameters are used in daily detail at design stage)

3. c-Si PV panels are expected to make production 4264 hours, mc-Si PV panels 4265 hours and a-Si PVs 4178 hours in large and small sizes throughout the year.

4. Total number of PV modules calculated are 2000 for crystalline ones and 1400 for thin film one. One PV module area is ~1.5 m^2 for single and multi crystalline ones but ~5 m^2 for a-Si. So total PV panel area is 3000 m^2 for crystalline ones and 6600 m^2 for thin film one.

5. Connection of PV modules each other in serial and parallel [16 x 125] for c-Si, [15 x 133] for mc-Si and [11 x 126] for a-Si.

6. There is a production 643 MWh/year in c-Si; 629 MWh/year in mc-Si; 674 MWh/year in a-Si simulations. Of meeting the load rate (solar fraction), an over rate such as 1.54 on an annual basis is for c-Si, 1.51 solar fraction is for mc-Si and 1.62 solar fraction is for a-Si simulations.

7. Although maximum power point (MPP) voltage in centigrade degree of 60 is 21 V for c-Si, 23 V for mc-Si and 32 V for a-Si, open circuit voltage in centigrade degree of -10 is 37 V for c-Si and mc-Si, and 50 V for a-Si.

8. Array efficiency is similar both single and multi crystalline types (~12 %) but the lowest rate in a-Si (5.5 %). System efficiency is also similar for c-Si and mc-Si (~11.8 %) and the lowest rate again in a-Si (5.4 %) (Fig. 7).

9. Special production of the system is the biggest for a-Si, 1689 kWh/kWp/year; second for c-Si, 1607 kWh/kWp/year; the lowest for mc-Si, 1570 kWh/kWp/year (Fig. 8). The average per kWp of electricity generation (system yield) is 4.40 kWh/kWp/day for c-Si; 4.30 kWh/kWp/day for mc-Si; 4.63 kWh/kWp/day for a-Si simulations (Fig. 9).

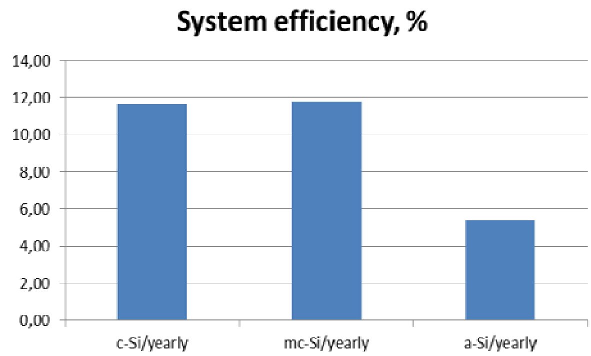

Fig. 7. System efficiency.

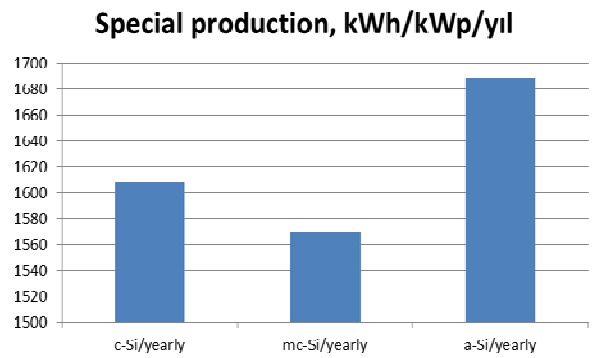

Fig. 8. Special production.

Table 3. Grid-connected fixed angle PV system indicators.

	Parameters	c-Si/annual	mc-Si/annual	a-Si/annual
PV module	PV brand	Yocasol	Kyocera	Parabel
	PV model	PCA 200	KC 200 GHT2	Uniflat 288
	PV panel angels, degree	15	15	15
	Azimut angel, degree	0	0	0
	Albedo	0.33	0.33	0.33
	P (nominal power), W	200	200	288
	I (short circuit, STC), A	8.68	8.21	10.6
	I (max. power point), A	7.78	7.55	8.72
	Temperature coefficient, % / °C	0.05	0.04	0.05
	V (open circuit), V	32.8	32.9	46.2
	V (max. power point), V	25.7	26.5	33
	Number of cells in module	54	54	44
Design parameters	Wind velocity, m/s	3.0	3.0	3.0
	Ambient temperature, °C	10.6	10.6	10.6
	Horizontal global irradiation, kWh/m²	1742.7	1742.7	1742.7
	Incident global irradiation, kWh/m²	1891.2	1891.2	1891.2
	Transposition factor	1.085	1.085	1.085
	Duration of production of the array, hour	4264	4265	4178
PV system	Number of modules	2000	1995	1386
	Total area, m²	2916	2814	6592
	Area of modules, m²	1.46	1.41	4.76
	Number of inverter / type	1	1	1
	PV nominal power, kWp	400	400	399
	PV max. power point, kWp	373	383	413
	AA nominal power, kWAA	400	400	400
	V (max. power point, 60 °C), V	20.8	22.6	31.5
	V (open circuit, -10 °C), V	37.3	36.7	49.6
	Modules on serial	16	15	11
	Number of string	125	133	126
	I (max. power point, STC), A	1058	1075	1152
	I (short circuit, STC), A	1085	1092	1335
	I (short circuit, max.), A	1180	1184	1450
	Array voltage, V	6.3	6.0	9.5
	Array current, kAh	1721	1862	1848
	Load demand, MWh	416.3	416.3	416.3
	Array efficiency, %	11.9	12.0	5.5
	System efficiency, %	11.7	11.8	5.4
	Solar fraction	1.54	1.51	1.62
	Max. operating power, kW	373	383	399
Inverter input	V (max. power point, 60 °C), V	333	339	347
	V (max. power point, 20 °C), V	416	407	398
	V (open circuit, -10 °C), V	597	551	545
Main results	System production, MWh/year	643	629	674
	Special production, kWh/kWp/year	1608	1570	1689
	Performance ratio	0.85	0.83	0.89
	System yield, kWh/kWp/day	4.40	4.30	4.63
	Loss of string, kWh/kWp/day	0.69	0.79	0.46
	Loss of system, kWh/kWp/day	0.09	0.09	0.09
	Investment cost, €/Wp	5.31	4.96	4.84
	Cost per unit, €/kWh	0.23	0.22	0.20

10. Performance ratios of the system with the PV modules of single, multi and amorf ones are 0.85, 0.83, and 0.89 respectively.

11. Loss of string is the lowest for a-Si, 0.46 kWh/kWp/year; second for c-Si, 0.69 kWh/kWp/year; the highest for mc-Si, 0.79 kWh/kWp/year. And loss of whole PV system is 0.09 for all.

12. Accordingly investment cost and cost per unit are minimum for a-Si, 4.84 €/kWp and 0.20 €/kWh; second for mc-Si, 4.96 €/kWp and 0.22 €/kWh; maximum for c-Si, 5.31 €/kWp and 0.23 €/kWh in 2010 exchange rates (Fig. 10).

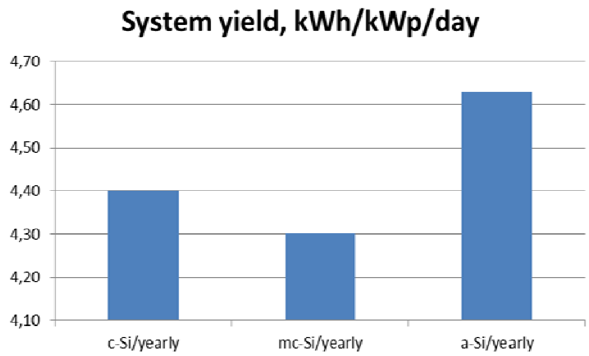

Fig. 9. System yield.

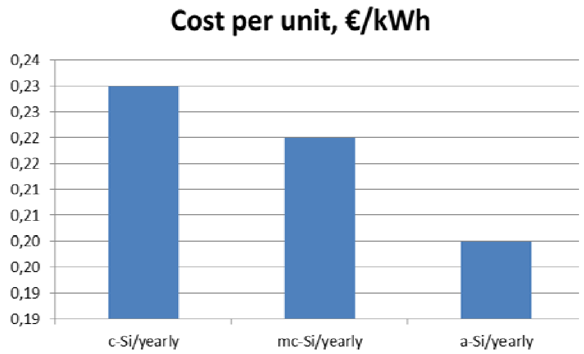

Fig. 10. Cost per unit.

4. Conclusions

As it is seen in main results table (Table 3), there is an increase of 8.5 % in addition to the horizontal plane as meteorological total solar radiation, mainly because solar panels is positioned at a vertical angle. Whereas technical solar energy potential is greater than solar atlas at the rate of almost 10 %, these data only contain direct and diffuse irradiation on air not albedo [8]. PV panel angles can be changed by reference load time throughout the year. If there is no obstacle, azimuth always should be taken 0, especially in countrysides. Albedo rate can be changed depending on surface reflectability.

Remembering that theoretical sunshine duration is 4454 hours/year [9], and measured sunshine duration is 2607 hours/year, PV systems would generate electricity even without direct sun thanks to diffused and reflected radiation from air and ground. All projections are designed to be load-call ratio for all ≥ 1, corresponds to a total energy consumption of 416 MWh/year, on behalf of all days to meet the load.

System yield can give an idea for technical designers in the unit of kWh/kWp/day not only for Ankara but also for Central of Turkey. PV manufacturers give reference values in the condition of STC, so this misleads people. PV system with the PV modules of a-Si is more suitable in economical and technical terms than others for electricity consumption behaviour of an agricultural farm and its environmental conditions. In a-Si type simulation, there are fewer modules than crystalline ones so junction parts also fewer. This difference decreases the efficiency loss in strings. If no area limit like agricultural fields, a-Si thin film PV modules can be chosen for PV systems. Investment cost and cost per unit value can encourage decision makers and investors.

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*Corresponding author: dr.yalcinlevent@gmail.com