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Designing, Simulating and Technical Analysis of a 2 MW On-grid Photovoltaic System for Agricultural Applications

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INFO

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ABSTRACT

The aim of this paper was to analyze technical analysis of agrivoltaic system in Kerman using PVsyst. A 2 MW photovoltaic system was developed for the grid-connected system. Meteonorm 7 software was used to get the meteorological data for the city of Kerman. PV loss resulting from variations of irradiance intensity and temperature and the inverter losses due to the operation were determined. The energy that can be generated throughout the year was calculated for each month considering the PV-array collection loss and system loss, i.e., inverter loss. The corresponding performance ratio was also determined for the energy output per month. Incident irradiation distribution, system output power distribution, array voltage distribution, and array temperature distribution were reported. Finally, parameter optimization tool was used to study the effect of tilt and azimuth. The tilt angle and the azimuth angle were 30º and 0º, respectively. The amount of annual energy injected into the grid was found to be 3766.321 MWh. The maximum energy injected into the grid was in August with 359.713 MWh, and the lowest energy was is in February with 264.412 MWh. As a result, an average annual performance ratio of 80.80% was achieved.

INTRODUCTION

The increase in population and energy demand, the reduction of fossil fuels and the resulting pollution have led to the movement towards using renewable energies (Azam et al., 2022). As well as sustainable energy supply, reducing the emission of environmental pollutants and avoiding global warming are among the current concerns of human societies (Rezvani et al., 2022). The rate of CO_2 emitted from burning fossil fuels to produce energy accounts for about 38% of total CO_2 emissions (Azam et al., 2022). The production of electric energy of 1 kWh using fossil fuels is about 475 g of CO_2 (Coşgun, 2021). The renewable energy in Iran, especially the solar radiation, has high potential. The solar radiation reduces a significant amount of carbon dioxide in the air by reducing the use of fossil fuels and the cost of electricity consumption.

Photovoltaic systems and wind turbines have become noteworthy options for providing electrical energy due to their affordable price and also, lack of dependence on the main energy grid. In recent years, the exploitation of these resources has faced unprecedented growth. The time and amount of capital return of the exploitation of these systems is a factor that has attracted the attention of investors to these projects and the installation of these resources, even on a small scale (Lei et al., 2020).

The big problem with solar power in the renewable energy sector is its heavy need for land to maximize power generation to meaningful levels. Various solutions have been developed under the name agrivoltaic (agrophotovoltaic or agrisolar), which focus on creating a proper dual use of the land, in a way that allows two production processes to be active without disturbing each other (Dinesh et al., 2016). Therefore, the design of agrivoltaic installations may require trade-offs with objectives such as optimizing product performance, quality and energy production. However, in some cases, the crop yield is increased due to the shade of the solar panels, which reduces some of the stress caused by high temperatures and UV damage on the plants (Al Mamun et al., 2022). Agrivoltaic systems are jointly developing the same area of land for solar photovoltaic energy as well as for agriculture. This new technology promises to improve food production and use less water, while also recovering energy (Coşgun, 2021). There are different types of PV systems as Grid-Connected, stand-alone, and Hybrid/Grid (Awasthi et al., 2020). In the following, some studies about PV are given.

A study evaluated the performance of the PV system grid-connected to Karunya University's electricity production, with a maximum power of 20.0 kW and a voltage of 17 V with PVsyst software. Polycrystalline silicon photovoltaic modules in 13 strings were used each string containing 10 PV modules connected in series with a power of 20.8 kW (Shrivastava et al., 2021). In a research to investigate the feasibility of installing a photovoltaic system for an educational institution, a grid-connected photovoltaic system of 100

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kW/s network including 323 PV Si-pol modules in 17 strings, each string having 19 modules, was simulated using PVsyst software. The proposed system produces 165.38 MWh/year. The annual efficiency ratio is about 80%, and the normalized output of the inverter or the final efficiency of the system (useful energy) is 4.42 kWh/kWp/day (Kumar et al., 2017). In a research, a stand-alone PV system was designed and installed for Bikaner University using PVsyst software. The average annual energy requirement in the mechanical engineering department was 1.086 MWh and the available energy through the solar panels was found to be 1.144 MWh (Kumar et al., 2021).

One of the widest use of solar PV panel systems in agricultural and bio systems engineering applications can be seen in irrigation due to the fact that they are cost-effective, environmentally friendly, reliable and have long life span (Verma et al., 2021; Chandel et al., 2015). Other uses are found in greenhouse engineering and agricultural buildings/structures to reduce the energy load of the ventilation, cooling or heating systems (Marucci et al., 2018). For instance, a 2.2 MWp solar photovoltaic plant has been proposed for Mohgra oasis in northern Egypt recently (Afrik21, 2022). Irrigation unions or private companies also seem to be interested in utilizing solar energy to generate electricity for the canal and well pumps (CEQA, 2022).

The use of solar panels for agriculture is promising when heat stress needs to be reduced on crops or for creating shades for livestock, reducing the evapotranspiration and hence enhancing the water use efficiency (Youngquist, 2019). Some studies were reported that solar arrays above the ground can provide cooler microclimatic conditions around the panels.

Therefore, it may be argued that electricity generation for supplying power for agri- and biosystem-based applications will gain more importance in the future. The use of solar PV systems to meet the energy demand is even more critical in remote areas lacking an electrical network. Widening the use of PV systems in this regard may allow, for instance, remote farms/enterprises to develop or vary their farming systems with the availability of affordable renewable energy. Compatibility of crops and solar panels should be taken into account in different regards in agricultural uses (Aroca-Delgado, 2018). Furthermore, agrivoltaic PV systems are promising to increase the water use efficiency and biomass of grasses and to provide shade for livestock. Thus, the aim of this study was to design and simulate the use of a 2 MW on-grid PV system at Kerman province using PVsyst software to meet relatively high levels of energy demand for regional or sub-regional irrigation systems run by unions, government, or related agri-industry.

RESEARCH METHODOLOGY

System design

The different stages of designing and simulating the on-grid PV system are as follows.

Geographical location

Meteorological data was obtained using Meteonorm 7 software at latitude 30.25º, longitude 57.10º, and altitude 1771 m. Sunny hours are the most important climate parameter to determine the amount of solar energy to be utilized. The maximum and minimum solar radiation occurs in August and December, respectively for the study area as shown in Fig. 1. The solar radiation is distinctively high at the period from May to August compared to the rest of the year. The amount of solar radiation increased at a high rate from January to May and decreased rapidly from August to December. It may be roughly said that the amount of solar radiation doubled (about 230 kWh/m^2) in the peak season compared to the period with the lowest radiation (110-120 kWh/m^2.)

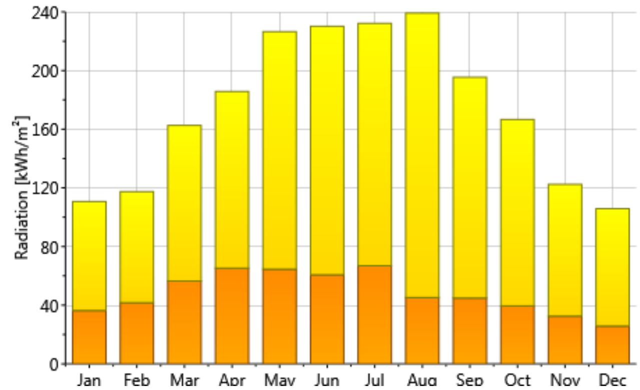

Fig 1. The solar radiation in different months in the city of Kerman, Iran

Azimuth and tilt angle

The azimuth angle determines the direction of the sun. Since the panels are located in the northern hemisphere facing south, this angle is considered zero.

The tilt angle is defined as the angle at which the solar panels face the sun. Sun's position changes every day with respect to the earth, so the installation angles of the panels also need to change. The most appropriate tilt angle is obtained by considering the transparent factor, loss by respect to optimum and the global on collector plane (Table 1). In general, the tilt angle is considered equal to the latitude of the location of interest (Kacira et al., 2004), corresponding to 30° for this study.

Table 1. The effect of different tilt angles

Panel tilt	Transparent factor	Loss by respect to optimum (%)	Global on collector plane (kWh/m^2)
20	1.11	-1.2	2333
25	1.12	-0.3	2355
30	1.13	0	2363
35	1.12	-0.3	2356
40	1.11	-1.2	2334

Albedo value

Albedo is related to the reflection of light from the earth's surface, which depends on the earth's surface cover. Its values range from 0.1 to 0.9. In this study, the reflection coefficient value was chosen to be 0.2 for grass.

Module and inverter specifications

Module and inverter are the most important components of grid-connected power plant. Based on initial cost, reliability, optimal use of the land area, panel type, output power and strength, the initial design is necessary.

From the selection section of the software module, YL310P-35b silicon-polycrystalline model manufactured by the company Yingli Solar with a rated power of 310 Wp was selected. Table 2 describes the technical specifications of the selected module at standard conditions (radiation of 1000 W/m^2, temperature of 25 °C).

Table 2. Description of Yingli Solar, YL310P-35b

Length	1.96 m
Width	0.99 m
Thickness	0.04 m
Weight	25.5 kg
Module area	1.940 m^2
Open circuit V_{OC}	45.70 V
Short-circuit current I_{SC}	8.986 A
Current max power point I_{mp}	8.407 A
Voltage max power point V_{mp}	36.7 V
Efficiency of module	15.98%

The inverter converts the DC power from the solar module to the AC power source. Matching the inverter specifications with the solar specifications is very important for the proper operation of the system. For the present research, considering the size of solar arrays, a 100 kW inverter was selected. The specifications of the inverter (Jema IF100TL) are given in Table 3.

Table 3. The specifications of the inverter of Jema IF100TL

Minimum MPP Voltage	410 V
Maximum MPP Voltage	750 V
Absolute max. PV Voltage	900 V
Maximum PV Power	120 kW
Maximum PV Current	250 A

The grid system configuration is shown in Fig. 2. The number of modules required to provide 2 MW power is 6450. According to the output power of the inverter, the number of necessary inverters is 17. In this case, overload is 0.1%. The number of strings in which the modules are connected in series is equal to 430 strings, and there are 15 modules in each string. The total area covered by the whole system is 12516 m^2.

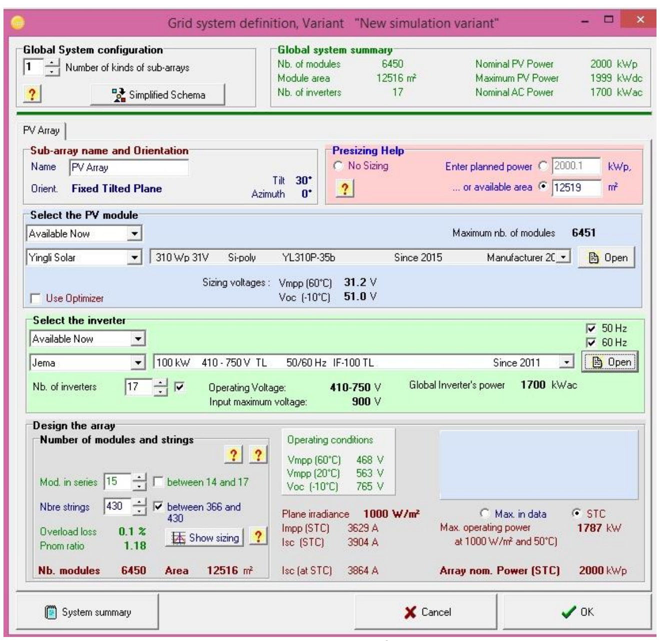

Fig 2. The grid system configuration

The performance of the grid system was analyzed by simulating the postulated grid system configuration. Normalized production per installed nominal power, performance ratio of the PV system, expected energy losses and the energy injected into the grid system were determined.

RESULTS AND DISCUSSIONS

Fig. 3 shows the changes in total daily radiation intensity based on the average data collected from 2020 for the city of Kerman during one year, which was extracted from Meteonorm7 software.

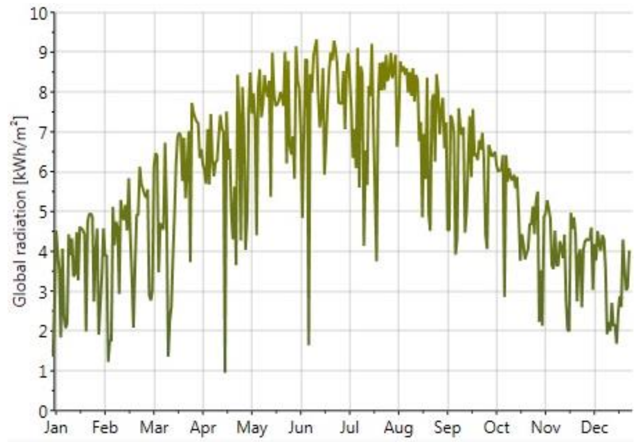

Fig 3. The changes in total daily radiation intensity

Fig. 4 shows the ratio of the normalized production per installed nominal power 2000 kWp in for one year. This diagram is equivalent to the daily energy produced by the designed photovoltaic system in different months of the year, which is scaled according to the rated power of the power plant. Part of this energy is lost in the parts of the photovoltaic panels, inverters and other equipment.

This Fig. depicts the proportions of collection loss and the system loss in the normalized energy. System loss constituted a small portion of the total loss while collection loss accounted for the majority of the losses. The red part of Fig. 4 shows the amount of useful energy produced by the system throughout the year. The amount of energy produced in spring and summer was higher. This energy may be utilized to run canal and well pumps for irrigation as well as meeting the energy requirements of ventilation and cooling systems of remote agricultural structures and buildings. In areas where electricity is available, the proposed system can help be used as a backup for blackouts during the summer.

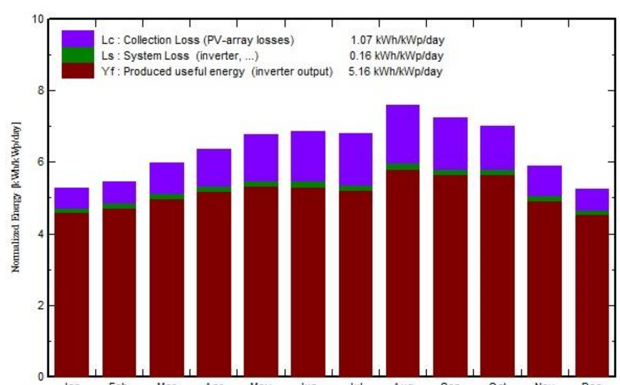

Fig 4. Normalized production per installed nominal power 2000 kWp

The performance ratio of the photovoltaic solar system is one of the important indicators in evaluating the system (Bhuvaneswari et al., 2022). For a grid-connected photovoltaic solar system, an annual efficiency ratio between 75 and 85% is desirable. Fig. 5 shows the variation of performance ratio of the PV system designed in this study. The temperature of the photovoltaic modules increases during the summer months, causing a reduction in the performance ratio (Mitavachan et al., 2011). This is shown in Fig. 5 by the gradual decrease towards summer and then increase towards winter months. An average annual performance ratio of 80.80% was achieved for the simulated PV system, which was in the acceptable range of efficiency ratio (Bhuvaneswari et al., 2022). The highest and lowest performance ratios were approximately 88% in the months of January and December and 77% in the months of July and August, respectively. Mitavachan et al. (2011) reported an efficiency decrease from 14.5% at 30 °C to 11.5% at 55 °C, explaining that efficiency of the modules was affected by the variations of the temperatures of the modules.

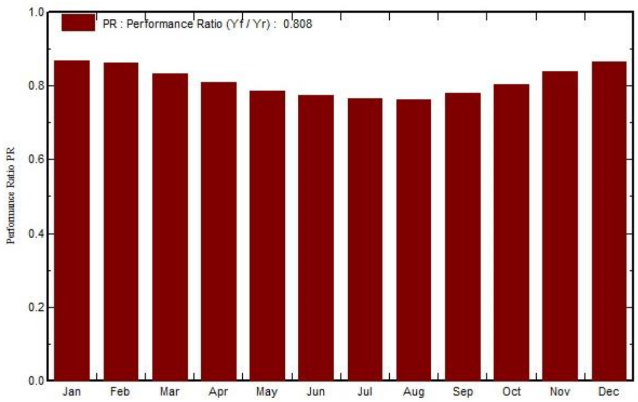

Fig 5. The performance ratio of the photovoltaic solar system designed

The outputs of the simulation are given in Table 4. The main results include horizontal global irradiation (GlobHor), ambient temperature (T_Amb), global irradiance on the collector plane without any optical corrections (GlobInc), effective global irradiance considering soiling losses and shading losses (GlobEff), effective energy at the output of the array (EArray), energy injected into the grid (E_Grid), efficiency Eout array/rough area (EffArrR), and efficiency Eout system/ rough area (EffSysR).

Yearly sum of global irradiation on the horizontal plane was 2099.4 kWh/m^2 Incident global irradiation in the collector plane and effective global (excluding all optical losses) were 2330.4 kWh/m^2 and 2266.9 kWh/m^2, respectively. The yearly energy produced by the PV modules and yearly energy injected into the grid were found to be 3879829 kWh and 3766321 kWh, respectively. The yearly average efficiency of PV modules about 13.03 % and the yearly average efficiency of the system was 12.91%. Table 4 demonstrates that all the parameters other than the efficiency terms (EffArrR and EffSysR) varied proportionally with the ambient temperature. The maximum values of all factors related to the global irradiance belonged to the late spring, the summer and early autumn. Efficiency terms were inversely proportional to the ambient temperature in Table 4 due to the reduction of the performance ratio with increasing temperatures of the photovoltaic modules, as explained before.

The diagram in Fig. 6 obtained for the postulated PV design shows the losses in the system. The global irradiance on the horizontal plane was 2.099 MWh/m^2. After applying the system losses, 3766321 kWh is injected into the grid, which can be reduced by changing the design parameters.

Kumar et al. (2017) simulated a 100 kWp PV system using the same software used in the current study and found that the system generates 165.38 MWh/year, out of which only 161.6 MWh/year is injected into the grid. The authors found an annual performance ratio around 80%. The same performance ratio was obtained in the current study. According to a current experimental study, the growth of the crop produced in the agrivoltaic was found to be comparable to that of the crop grown in the open sky (Waghmare et al., 2022). An agrivoltaic system of 1 MW was produced 215520 kWh and 176400 kWh more electricity than that of a standard solar PV plant at two different heights above the plants. It was stated that with the additional benefit of increased power generation, the same plot of land would be used to grow spinach or other high-yielding crops. Kostik et al. (2020) explained that using agrivoltaics for combined use of land can increase the crop productivity by 45%-70% according to Land Equivalent Ratio.

As stated before, the production of each 1 kWh of electricity using fossil fuels produces about 475 g of carbon dioxide. In the current study, 3766321 kWh was injected into the grid annually, which could reduce the emission of 1,789,000 kg of carbon dioxide during the year. Pascaris et al. (2021) conducted an LCA and exclaimed that integrated solar and pasture-based agricultural systems are superior to traditional practices due to their lower emission and energy intensity. According to the authors, the pasture-based agrivoltaic system produced about 70 % less emissions and demanded about 83% less fossil energy compared to non-integrated production.

This study showed that under the meteorological conditions of the city of Kerman, it is likely to generate electricity with good performance. The previous researchers have demonstrated that the agrivoltaic systems are able to provide good results due to the combined effect of electricity generation and crop production under the agrivoltaic panels. Thus, it may be suggested that further research should focus both theoretically and experimentally on the potential effects of agrivoltaic systems on crop yields under different growing conditions in the Kerman province. Since the total area of the panels is about 1.25 ha, the agrovoltaic system can be installed over 2 ha cropland areas with different configurations.

Table 4. The outputs of the PV 2 MW designed system

	GlobHor kWh/m^2	TAmb °C	GlobInc kWh/m^2	GlobEff kWh/m^2	EArray kWh	E_Grid kWh	EffArrR %	EffSysR %
January	110.8	5.01	163.8	160.0	292837	284452	14.28	13.87
February	117.7	8.49	153.1	149.3	272001	264412	14.2	13.8
March	161.1	13.38	185.5	180.6	317986	308641	13.7	13.3
April	186.2	18.31	191.4	185.7	320043	310529	13.36	12.96
May	227.7	23.86	210.0	203.4	340317	330279	12.95	12.56
June	232.7	27.33	206.0	199.0	329021	319154	12.76	12.38
July	232.9	29.09	210.8	204.0	332758	322735	12.61	12.23
August	238.7	27.00	235.8	229.2	370902	359713	12.57	12.19
September	196.1	23.21	217.6	212.2	349067	339079	12.82	12.45
October	167.3	18.07	217.5	212.5	360502	350129	13.24	12.86
November	122.0	11.06	176.5	172.7	305194	296175	13.81	13.40
December	106.1	6.7	162.3	158.4	289202	281024	14.24	13.83
Year	2099.4	17.68	2330.4	2266.9	3879829	3766321	13.30	12.91

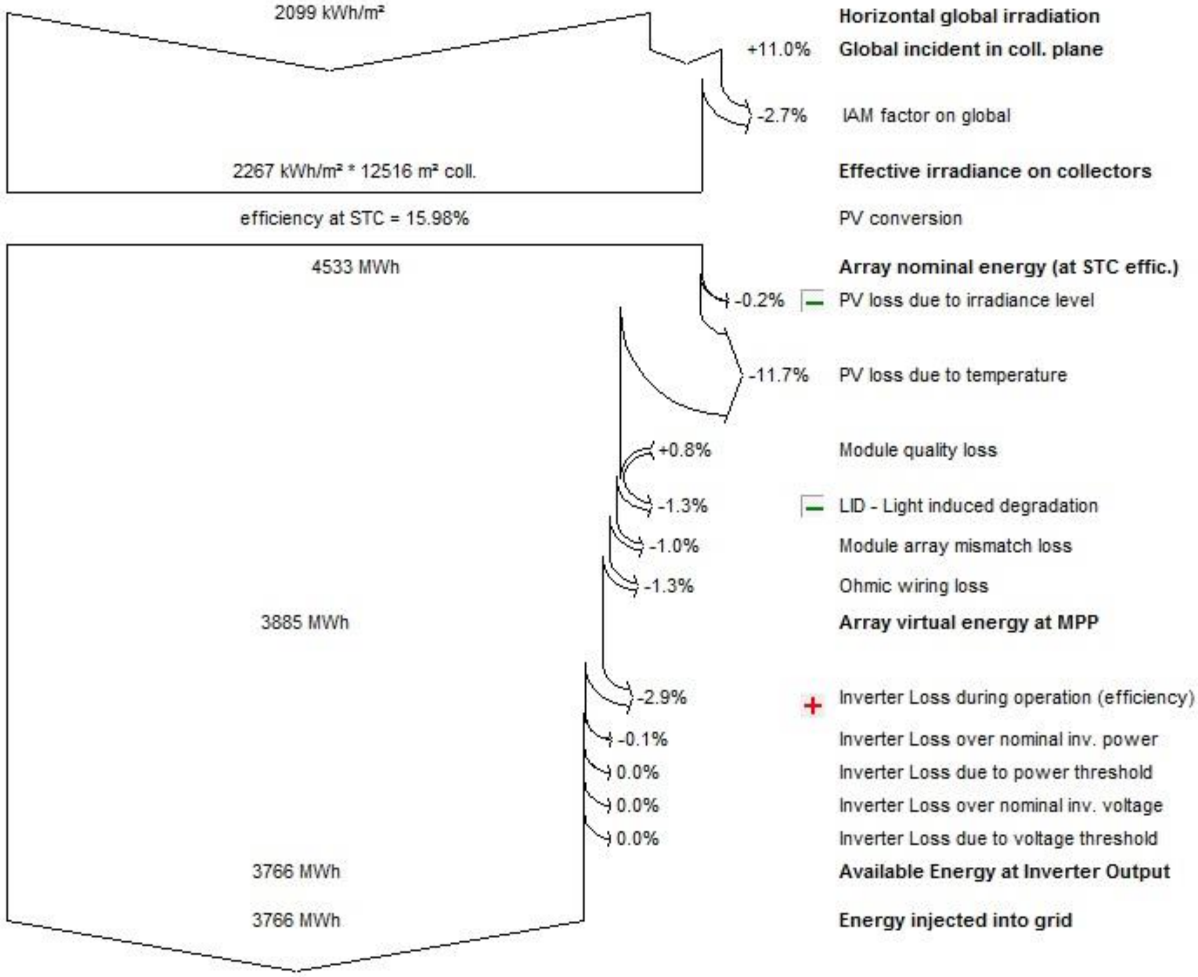

Fig 6. The loss diagram of the designed PV system over the whole year

CONCLUSIONS

The followings can be summarized and concluded as a result of this study:

- A 2 MW power plant using panel systems was modeled and its performance was simulated using PVsyst software for agrivoltaic purposes in Kerman province, Iran.
- The tilt angle and the azimuth angle were 30° and 0°, respectively for the study area.
- The amount of annual energy injected into the grid was 3766321 kWh.
- The maximum energy injected into the grid in August was 359713 kWh, and the lowest energy was in February with 264412 kWh.
- An average annual performance ratio of 80.80% was obtained, which was comparable to previous studies.

For future studies, it may be recommended that different configurations of the panels be tested, in terms of distances between neighboring panels, for different shading patterns on production fields. Field experiments may be conducted with different crops to determine the effect of various panel constellations on the yield, energy production per unit land area, and cost of investment for each scenario.

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