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Evaluation of Fixed and Single-Axis Tracking Photovoltaic Systems Using Modeling Tool and Field Testing

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A B S T R A C T

One of the main issues to build a photovoltaic plant is to specify the type of mounting structure used for solar panels. Making a proper choice for the structure type is crucial to harvest the maximum performance from the PV plant. In this paper, two of the most common types of structures have been investigated by analyzing two 2.4 kW PV systems. One system has a fixed structure and the other one has a single vertical-axis structure. The energy production, performance ratio and final yield of both systems have been monitored, analyzed and compared over a one-year period. Performance of PV plants is often predicted by modeling tools prior to the construction of plant and the results of simulations are usually considered as a reliable source to design a PV plant and supply the equipment. Thus, the accuracy of modeling tool results are vital for both investors and installers. Therefore, PVsyst as one of the most commonly used modeling tools has been studied by simulating both PV systems and comparing the predicted and measured data. The error margin of simulations has been within the range of 1%, 3% and 1% for generated energy, performance ratio and final yield respectively, and the tracker system generated 28% more energy compared to fixed system in one year.

1. Introduction

Concerning the global warming problem and rising air pollution, the demand for renewable energy and especially solar energy is more than ever before. The declining rate of construction expenses of photovoltaic plants which is getting very close to that of fossil fuel power plants has made the investment in photovoltaic energy more profitable than before. Achieving the goals of international agreements aiming at reducing the greenhouse gases such as Paris agreement, requires more global effort to develop solar energy. Prior to the planning and constructing a PV plant, a feasibility study has to be carried out in order to meet all the economic and technical aspects of the PV plant. In general, there are different direct and indirect factors which have effect on the feasibility and profitability of construction of a PV plant, such as economy status of the country, electricity tariffs, tax, energy regulations, technology, market, the level of irradiance in the region of PV plant and the yield of PV plant. [1] Clearly, performance, and generated energy of a PV system are among the required parameters to perform a feasibility study. These parameters depend on meteorological status and technical parameters such as system components and the type of solar panels structure. Designing a PV plant is often carried out using modeling tools by which the modeling, simulation and economic evaluation of the plant are performed.

As mentioned, one of the effective factors on energy production and eventually the revenue of a PV plant is the type of solar panel mounting structure. Structures are mainly built either with a fixed form or with tracking ability. Fixed structures are generally in two types. Permanent or seasonal structures which are fixed or can be reoriented by change of seasons. Tracking structures are also built with one or two axes. It is obvious that tracking systems can produce relatively more energy compared to fixed ones, but since they require more budget both in building and maintenance phases, they have a less share among the solar plants. Choosing a tracking structure over a fixed one for a PV plant depends on meteorological and irradiance status of the location, expenses, and the total revenue of the PV system. As a rule of thumb, utilizing a tracker structure is only justified when the revenue difference between two types of structures over the life time of plant, exceeds the difference in construction and maintenance expenses. A quantitative outcome of this rule depends on abovementioned economic factors which differ in every country. Thus, comparing the energy generation of the two structures, provides the investors with valuable data for planning a PV plant construction. Several papers [2,3,4,5,6] have compared the results of modeling tools and measured data for PV plants on different locations. Comparing the performance of fixed and dual-axis systems has been carried out in [7], while [8] has studied the yield of different types of tracking systems. In this paper, fixed and single-axis tracking systems have been investigated as most abundant PV structures, using measurements and modeling tools.

2. Modeling tools

There are various modeling tools for simulating and analyzing PV plants, both technically and economically. Having a reliable tool with a predictable range of error assists us to predict and evaluate the performance of PV plants before the construction. The prediction of PV plant outcome provides useful information for installers and users about the desirable performance of the system, which can be very helpful in cases in which the plant is not working properly. Five PV tools, which are used generally in the PV industry and researches are as below:

- PV*SOL Expert
- PVsyst
- SAM
- PVWatts
- RETScreen

PV*SOL and PVsyst are high detailed tools for studying, modeling, designing and analyzing the PV systems. SAM provides an accurate model for operation and financial evaluation of renewable energy power plants including PV plants. PVWatts is a simple tool to assess the PV system, which is helpful for initial feasibility studies. RETScreen facilitates a numerical analysis for financial modeling of PV plant and enables the user to perform a feasibility study both technically and financially. PVWatts and RETScreen need fewer system parameters as input data and have a simpler performance. They are only appropriate for primary feasibility study of the PV plant, while PV*SOL, PVsyst and SAM provide a more accurate simulation by receiving more parameters as input. [4] In this paper, PVsyst has been used for modeling the PV systems.

3. Performance Parameters

Performance parameters of PV systems have been proposed by the international energy agency (IEA) to analyze the performance of PV plants. Various parameters have been presented for describing the total performance of the system based on energy production, irradiance levels and loss effects. Such as array yield (Ya), reference yield (Yr), final yield (Yf), Performance Ratio (PR), Capacity Utilization Factor (CUF), inverter efficiency and system efficiency. [3] Among these, the performance ratio (PR) and final yield (Yf) are very useful and common for evaluating the performance of PV systems. In this paper, these two parameters are predicted and measured for both PV systems.

3.2. Performance Ratio (PR)

Performance Ratio is a location-independent index to measure the performance quality of the PV system. Practically, this is not possible to reach a PR of 100% since unavoidable losses such as thermal loss occur as PV plant works. PR index depends on various environmental and technical factors such as modules temperature, solar irradiance, soiling, shading, power loss, period of measurements, connection losses and efficiency of modules and inverters. [9] This parameter demonstrates the level of performance and reliability of PV plant and provides the possibility to make a comparison between various PV plants or monitor the performance of a PV system during any given term.

To calculate the PR of PV plant, some meteorological and technical data such as irradiance level, efficiency and modules area are required. The equation 1 is used to calculate the performance ratio.

$$PR = \frac{E\ [kWh]}{GE\ \left[\frac{kWh}{m^2}\right] * A\ plant\ [m^2] * \eta\ module} \quad (1)$$

In this equation, E is the generated energy of PV plant, GE is global irradiance at location of PV plant, A is the area of solar modules, and η is efficiency of modules.

3.1. Final Yield (Yf)

The final yield of PV system is defined as net output energy of PV plant divided by the nameplate power of photovoltaic array, [10] and it is calculated using equation 2. This factor can provide the net amount of energy that one kilowatt of PV array can produce during any given period. The final yield is not dependent on the system size and it can be utilized to predict the energy production capability of PV systems of different scales.

$$Y_f = \frac{E\ [kWh_{AC}]}{P\ [kW_{DC}]} \qquad (2)$$

4. Measurements

In order to make a comparison between the performance of fixed and single-axis tracking systems as two popular mounting structures, a fixed PV system with 2.4 kW nominal power and a 2.4 kW vertical-axis (east-west) tracking system have been surveyed. Both systems are grid-connected, both have been built on the same location and use similar solar panels and inverters. The systems are built in city of Mashhad in the northeast of Iran. Both systems have 12 similar monocrystalline solar panels connected in a single string and a 2500 W grid-connected solar inverter. The output power, energy injected into the grid and irradiance have been monitored in 1 minute sequences over a one year period from July 2016 to July 2017. As [11] stated, evaluation of PVsyst results has shown to be within the predictable range of error compared to measured data, if the simulations are carried out in a one-year period. Shorter simulation terms lead to less accurate results.

From the total energy production of both systems, the final yield of PV systems as a major parameter to evaluate the PV plants in different locations have been calculated in one year. This is a useful index to predict the eventual energy production of any given PV system with the similar structure and equipment and in the same geographical region. The performance ratio of both systems also has been calculated using the data of irradiance and generated energy.

4.1. Measurement results

The fixed 2.4 kW system has a tilt angle of 35 degrees and azimuth angle of zero. The tracking system has a tilt angle of 42 degrees and a sweep angle of 82 degrees. Fixed system was on its third year of operation while the tracker was on its fifth year. Both used 12 similar monocrystalline solar panels and a 2500 W grid-connected inverter. Both systems were positioned in the same location and both were cleaned with the same practice. The final yield of fixed and tracking systems over a 12 months period are plotted in figures 1 and 2 respectively.

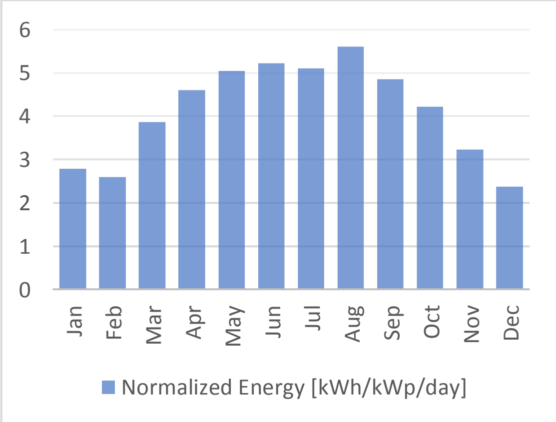

Fig.1 . Final yield of the fixed system

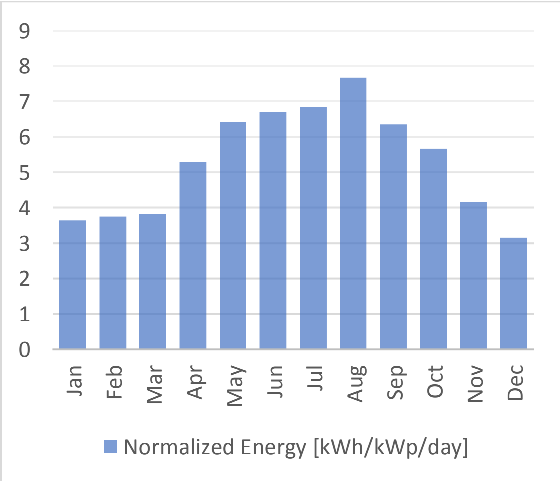

Fig.2 . Final yield of the tracking system

5. Simulation

Analyzing the simulation results and comparing them to measurement data is a useful method to assess the accuracy of simulation tools since in general, technical and economic aspects of a PV plant should be predicted before installing the PV system. Thus, in order to make a fair comparison between the measured data of PV systems and the simulation data, both systems were simulated with all the details using PVsyst 6.43 software. The final yield and performance ratio have been studied to provide the data for evaluating the modeling tool.

5.1. Simulation results

Simulations have been carried out based on operational conditions of both systems. The fixed and tracker systems were on their third and fifth year of operation respectively. The soiling rate was considered 3% for both as a proportional value and since the data have been monitored from inverters directly, AC loss was not considered in the simulations and shading is not assumed as well. Final yield of simulated fixed and tracking systems are depicted in figure 3 and 4 respectively.

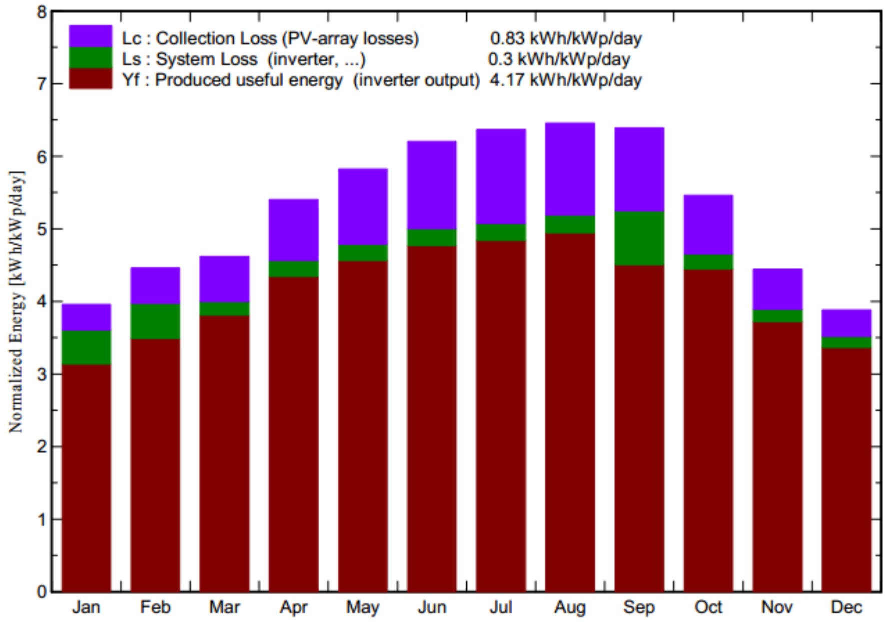

Fig.3 . Final yield, system loss and collection loss of simulated fixed system

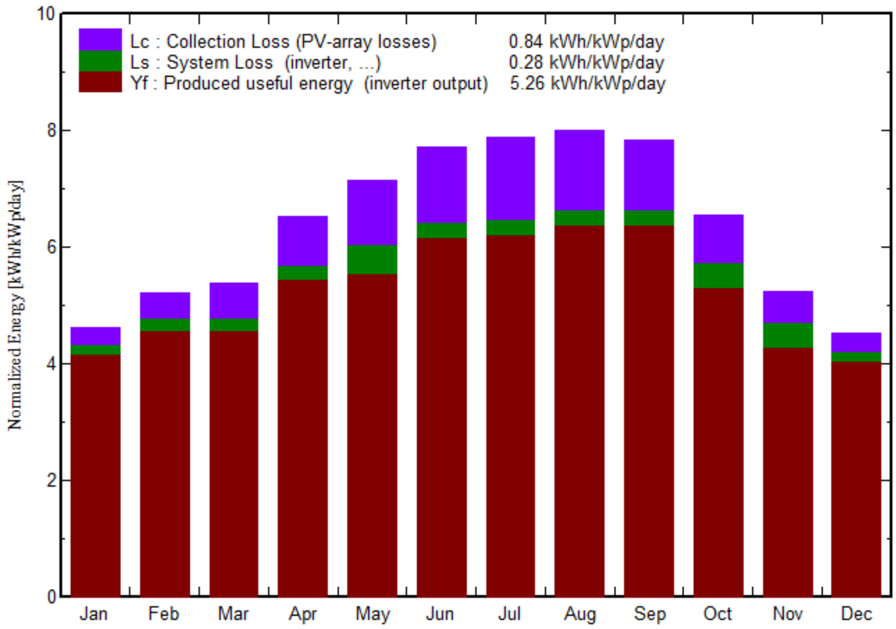

Fig.4 . Final yield, system loss and collection loss of simulated tracking system

6. Discussion

In order to evaluate the results of both PV systems and make a comparison between the function of fixed and tracking systems as well as comparing measured and predicted data, the generated energy, performance ratio and final yield of both systems have been demonstrated in the tables below. Table 1 lists the measured and simulation results of fixed and tracking systems. It depict that except for December and February in which the solar arrays of fixed system were covered by snow for up to 6 days, in the other months the tolerance of simulation error was under 15 percent with average of 7 percent (for all months excluding February and December). The total energy predicted by PVsyst was very close to the measured amount with only 0.7% error. The error of PR was 3% for the fixed structure and final yield shows only 0.9% error.

For the tracking system also the measured energy was not close to that of simulation on February and December because of snow. Moreover, in March the tracker did not track the sun due to some technical problems. Therefore, these three months are not appropriate to evaluate tracking ability of tracker system was inactive, for the rest the months the difference of energy under 16 percent with average of 7%. The annual generation between two systems changes from a the accuracy of simulation results. However, for the rest of months the error of simulation results was produced energy was only 0.9% above the simulation result.

Comparing the measured energy of fixed and tracker shows that except for March in which the minimum of 15% in April to a maximum of 44% in February. Overall, the tracker produced 28% more energy than the fixed system in the entire year.

Table.1 .Generated energy

	Fixed-Measured energy[kWh]	Fixed-Predicted energy[kWh]	Tracker-Measured energy[kWh]	Tracker-Predicted energy[kWh]
January	207.5	233.6	272.3	309.0
February	174.5	234.4	252.1	307.7
March	287.2	283.4	285.1	340.3
April	330.5	312.7	381.4	392.0
May	375.6	339.6	478.2	412.1
June	375.9	343.5	483.1	443.7
July	381.8	360.0	510.2	462.2
August	417.3	368.0	571.8	475.2
September	348.9	324.6	458.5	458.7
October	314.1	330.8	422.0	395.2
November	232.3	268.2	300.9	308.7
December	176.8	250.3	234.6	300.5
Yearly	**3622.4**	**3648.9**	**4650.2**	**4605.4**

Table 2 provides the calculated and predicted amounts of PR for both systems. According to these values, the measured performance ratio of tracking system was 5% more than that of fixed system, while the simulation results show 4% difference between the PR of two systems. The simulation error was within 3% for both systems.

Table.2 .Performance Ratio

	Measurement [%]	Simulation [%]
Fixed system	0.75	0.78
Tracking system	0.80	0.82

Table 3 shows the calculated and simulated values of final yield for both systems. Based on this, final yield of the single-axis tracking system is 1.17 hour more than fixed system and the simulation error was below 1% for both. This provides investors with a valuable information to compare the profitability of different PV systems with similar structures and in the same region.

Table.3 .Final Yield

	Measurement [hour]	Simulation [hour]
Fixed system	4.13	4.17
Tracking system	5.30	5.26

7. Conclusions

Comparing the results of simulation and measurements of both systems indicate that simulating the photovoltaic systems in scale of one year leads to notably more accurate and reliable results compared to simulating in scale of a month. This is mainly due to uncertainties of weather conditions in shorter periods of time. Moreover, Simulation of both fixed and single-axis tracking systems demonstrated very close results compared to measured parameters. The error of annual produced energy for simulation was under 1% in both cases, which was significantly below the rates of monthly error. Predicted PR factors were 3% and 2% above the calculated PR for fixed and tracker respectively. Final yield error was also below 1% for both systems. According to the results, PVsyst showed to be a reliable tool for simulating fixed and single-axis tracking PV systems in scale of a year. Comparing the fixed and single-axis tracking systems, the latter could generate 28% more energy in 1 year.

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