# Performance and Availability Analyses of PV Generation Systems in Taiwan

H. S. Huang, J. C. Jao, K. L. Yen, and C. T. Tsai

***Abstract*—**The purpose of this article applies the monthly final energy yield and failure data of 202 PV systems installed in Taiwan to analyze the PV operational performance and system availability. This data is collected by Industrial Technology Research Institute through manual records. Bad data detection and failure data estimation approaches are proposed to guarantee the quality of the received information. The performance ratio value and system availability are then calculated and compared with those of other countries. It is indicated that the average performance ratio of Taiwan's PV systems is 0.74 and the availability is 95.7%. These results are similar with those of Germany, Switzerland, Italy and Japan.

***Keywords*—**availability, performance ratio, PV system, Taiwan

## I. Introduction

DUE to the impact of global warming, the utilization of renewable energy has become one of major methods to reduce the quantity of $CO_2$ emission. Among various kinds of renewable energy, both the photovoltaic (PV) and wind generation systems are particularly recognized as the most glowing main forces. The PV systems are now installed throughout the world for many years. Except for promoting the quantity of PV systems, the quality of PV systems should be noted.The operational performance and system availability of PV systems become more and more important. In view of this, the International Energy Agency (IEA) established a group called team Task 2 in 1999 to collect PV operational data from IEA countries worldwide, such as Germany, Japan, Switzerland and Italy. This performance database can be used freely to study the PV system operational performance and cost related issues. For this time, the performance database contains high quality data of 505 PV plants with a capacity more than 13.5 MW [1].

In Taiwan, Industrial Technology Research Institute (ITRI) is authorized by the Bureau of Energy, Ministry of Economic Affairs to promote PV generation systems. From 2000 to 2009, 763 sets of PV generation system were established [2]. The owner for each PV system has to return monthly final energy yield and failure record for 5 years. These data can help us to understand sufficiently the operational performance and availability of PV systems. Then, the analyzed information can be used as a further reference for cost/benefit analysis of the PV systems installed in Taiwan. In this article, the operational performance and availability of PV systems in Taiwan are studied. Section 2 defines the performance and availability indices. Data manipulation approaches are provided in section 3. Section 4 shows the statistically analyzed results and discussions. Section 5 conclusions finish this article. Details are given in the following sections.

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## II. Performance and Availability Indices of PV Systems

### A. Performance Indices

There are many indices for assessing PV system performance. The final system yield $Y_f$ is the energy delivered to the load per day and kWp. The reference yield $Y_r$ is based on the in-plane irradiation and represents the theoretically available energy per day and kWp. The performance ratio $PR$ is the ratio of PV energy actually used to the energy theoretically available (i.e. $Y_f/Y_r$ ). The definitions of these indices are shown in Figure 1 and following equations [3]:

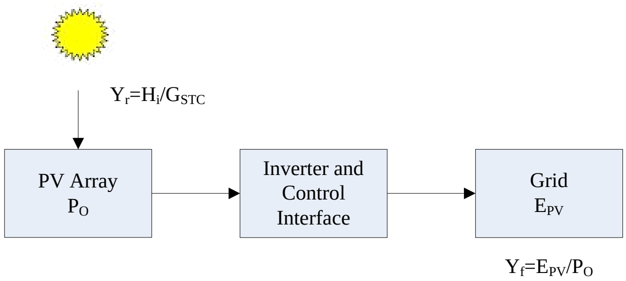


Fig. 1 Definitions of PV system performance indices

Final system yield

$$Y_f = E_{pv} / P_o \quad \text{(kWh/kWp*day) or (hours/day)} \qquad (1)$$

Reference yield

$$Y_r = H_i / G_{STC} \quad \text{(kWh/kWp*day) or (hours/day)} \qquad (2)$$

Performance ratio

$$PR = Y_f / Y_r \qquad (3)$$

Where

$E_{pv}$ : Energy delivered to the load (kWh)

$P_o$ : Norminal power of PV array at standard test conditions (kWp)

$H_i$ : Actual in-plane irradiation ($kWh/m^2$)

$G_{STC}$ : Reference in-plane irradiation at standard test conditions =$1kW/m^2$

The PR value is independent of location and system size and indicates the overall losses on the array's nominal power due to module temperature, incomplete utilization of irradiance and system component inefficiencies or failures [4]. Therefore, it is a necessary index to represent the operational performance of a PV system. According to the performance indices, the collected data can be statistically calculated and compared with each other to understand the performance characteristics of the studied systems.

### *B. Availability Indices*

The availability indices of PV system include Mean Time To Failure (MTTF), Mean Time To Repair (MTTR), Mean Time Between Failure (MTBF) and availability. MTBF is used to indicate the cycle time between failures. This value therefore exceeds the MTTF by a margin which is attributable to the time associated with repair. Their definitions are shown in Fig. 2 and following equations [5]:

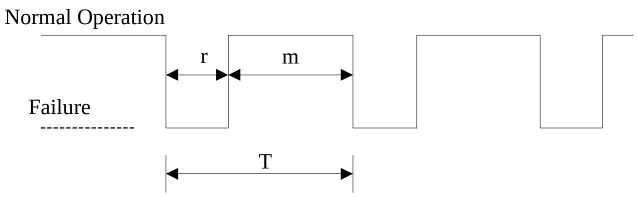


Fig. 2 Definitions of system availability indices

Mean time to failure $MTTF = m$ (year) (4)

Mean time to repair $MTTR = r$ (year) (5)

Mean time between failure $MTBF = m + r = T$ (year) (6)

Availability $$Availability = \frac{m}{m+r} = \frac{m}{T} \quad (7)$$

The fault tree of PV system availability is usually flat, since each component event may lead immediately to a system failure without requiring another component event to occur. In this article, the top event of the fault tree is defined as one PV array or whole the PV system enters failure state and requires repaired. The failure of computer or monitoring system doesn't count as a top event due to the generation of PV system still continuing.

## III. DATA MANIPULATION APPROACHES

### *A. Daily irradiation data*

Only the monthly final energy yields and failure records of PV systems are returned by PV owners or system companies. However, for calculating the performance indices, the irradiation data is necessary. Because ITRI doesn't force the owners to install solar irradiance sensor, the irradiation information is not collected. In this article, the measured irradiation data of weather stations by the Central Weather Bureau (CWB) in Taiwan is used to represent the irradiation information of the nearby PV systems. TABLE I shows the average daily irradiation data of various weather stations in Taiwan from years 2006 to 2008.

TABLE I
AVERAGE DAILY IRRADIATION DATA OF VARIOUS WEATHER STATIONS IN TAIWAN FROM YEARS 2006 TO 2008

| Station Name | Located City | 2006 Daily Irradiation ($kWh/m^2$) | 2007 Daily Irradiation ($kWh/ m^2$) | 2008 Daily Irradiation ($kWh/ m^2$) |
|---|---|---|---|---|
| Keelung | Keelung City | 870.10 | 865.02 | 976.28 |
| Pengjiayu | Keelung City | 1118.53 | 1283.90 | 1468.32 |
| Anbu | Taipei City | 1007.26 | 942.00 | 1068.71 |
| Taipei | Taipei City | 1050.92 | 1034.50 | 1115.40 |
| Zhuzihu | Taipei City | 715.01 | 704.38 | 758.83 |
| Banciao | New Taipei City | 1402.03 | 1087.80 | 1147.44 |
| Danshuei | New Taipei City | 1001.66 | 1030.36 | 1072.03 |
| Hsinchu | Hsinchu County | 1205.61 | 1224.45 | 1263.20 |
| Yilan | Yilan County | 1043.48 | 1032.91 | 1056.06 |
| Su-ao | Yilan County | 1073.91 | 883.46 | 1133.96 |
| Matsu | Lienchiang County | 1036.37 | 1098.59 | 1107.87 |
| Taichung | Taichung City | 1438.88 | 1486.99 | 1479.61 |
| Wuqi | Taichung County | 1233.39 | 1258.89 | 1296.01 |
| Sun Moon Lake | Nantou County | 1159.33 | 1185.98 | 1207.29 |
| Alishan | Chiayi County | 1158.32 | 1229.87 | 1246.47 |
| Yushan | Chiayi County | 1222.90 | 1401.66 | 1077.50 |
| Chiayi | Chiayi City | 1547.72 | 1609.34 | 1723.41 |
| Hualien | Hualien County | 834.59 | 1219.74 | 1240.21 |
| Dongjidao | Penghu County | 1224.78 | 1337.90 | 1519.70 |
| Penghu | Penghu County | 843.57 | 1132.85 | 1422.79 |
| Kinmen | Kinmen County | 1262.63 | 1295.78 | 1294.76 |
| Tainan | Tainan City | 1277.91 | 1402.03 | 1454.14 |
| Yongkang | Tainan County | 1353.73 | 1514.68 | 1316.86 |
| Cigu | Tainan County | 1408.58 | 1388.13 | 1388.02 |
| Kaohsiung | Kaohsiung City | 1391.13 | 1448.21 | 1471.65 |
| Hengchun | Pingtung County | 1455.94 | 1408.21 | 1379.56 |
| Taitung | Taitung County | 1524.60 | 1539.34 | 1562.92 |
| Chenggong | Taitung County | 1154.36 | 1168.21 | 1348.54 |
| Dawu | Taitung County | 1293.54 | 1288.86 | 1276.89 |
| Lanyu | Taitung County | 1103.16 | 1128.54 | 1061.20 |

### *B. Bad Data Detection and Failure Data Estimation*

It may happen that the collected data by ITRI presents unreasonable or short since it is returned from PV owners or system companies by handworks. In this article, for detecting the bad energy yield data and estimating the failure data, two approaches are proposed as followings:

(a) When the final system yield $Y_f$ is greater than 6 hours, this data is recognized as bad data and deleted.

(b) When the returned monthly final energy yield is zero and no failure report is recorded, it is recognized as failure for whole the month. When the returned monthly final energy yield is zero for successive several months, the failure event is recognized as once. The number of failure days for each month close to the zero-yield months is estimated as following:

$$failure\ days = \frac{E_p - E_r}{E_p} \times days\ of\ that\ month \quad \text{(days)} \quad (8)$$

Where

$E_p$ : Expected monthly energy yield (kWh/month)

$E_r$ : Returned monthly energy yield (kWh/month)

$$E_p = PR_m \times I_d \times P_o \quad \text{(kWh/month)} \quad (9)$$

$PR_m$ : The modified PR value that removes data from zero yield months and the two months before and after the zero yield months

$I_d$ : Average daily irradiation for that month

When the estimated failure days are negative, the number of failure days is recognized as zero.

## IV. Statistically Analysis Results and Discussions

Among the collected data by ITRI, 202 sets of grid-connected PV systems are selected and their performance and availability indices are then statistically calculated. These data is collected from years 2006 to 2008, totally three years. The base information of these PV systems is divided into three groups according to their geographical locations (latitudes) and shown in TABLE II.

TABLE II
Base Information of 202 PV Systems in Taiwan

| District | No. of systems | Total kWp capacity (kWp) | Average capacity per system (kWp) |
|---|---|---|---|
| Northern Taiwan | 64 | 492.902 | 7.7 |
| Central Taiwan | 71 | 710.316 | 10.0 |
| Southern Taiwan | 67 | 865.981 | 12.9 |

Note: (a)Northern Taiwan is defined as northern counties of Miaoli County (included)
(b)Central Taiwan is defined as northern counties of Chiayi (included) and southern counties of Miaoli County (not included)
(c)Southern Taiwan is defined as southern counties of Tainan (included)

### *A. Final system yield of PV systems*

The variation of final system yield for the PV systems in Taiwan is shown monthly in Fig. 3. From Fig. 3, it can be seen that the final system yields are varying between 2.0 and 3.5 hours. It is higher in summer and lower in winter, and gradually rising year by year. The average value is 2.24 hours in the northern Taiwan, 2.88 hours in the central Taiwan and 2.69 hours in the southern Taiwan. It is 2.61 hours in whole the Taiwan.

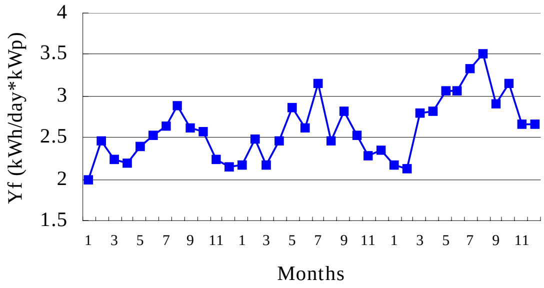


Fig. 3 The variation of final system yield for the PV systems in Taiwan

Fig. 4 shows the variation of irradiations measured from the weather stations of CWB in Taiwan monthly from years 2006 to 2008. Comparing Fig. 3 with Fig. 4, it can be found that there is a positive relationship between final system yield and irradiation.

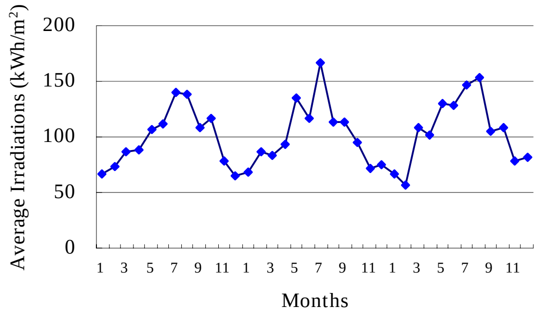


Fig. 4 The variation of irradiations measured from the weather stations of CWB in Taiwan

### *B. PR values of PV systems*

Fig. 5 shows the variation of PR values for PV systems in Taiwan monthly from years 2006 to 2008. From Fig. 5, it can be seen that the PR values are varying between 0.6 and 0.9. It is higher in winter, lower in summer, and gradually rising year by year. The average is 0.73 in northern Taiwan, 0.81 in central Taiwan and 0.71 in southern Taiwan. It is 0.74 in whole the Taiwan.

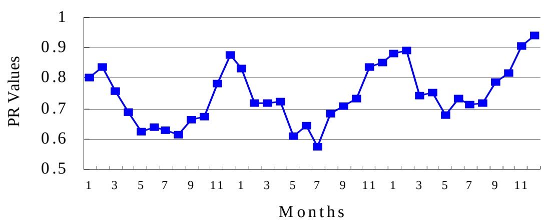


Fig. 5 The variation of PR values for PV systems in Taiwan

Fig. 6 shows the variation of average temperatures measured from the weather stations described in TABLE I monthly from years 2006 to 2008. Comparing Fig. 5 with Fig. 6, it can be found that there is a negative relationship between PR values and temperatures.

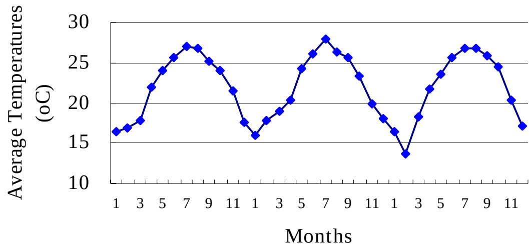


Fig. 6 The variation of average temperatures measured from the weather stations of CWB in Taiwan

*C. Availability of PV systems*

Fig. 7 shows the distribution of PV system availabilities calculated from years 2006 to 2008 in Taiwan. The average availability for all the PV systems is 95.7%. 70% of the PV systems have not encountered any failure event for all the three years. The causes of failures for the other 30% of the PV systems include inverter failure, PV module failure and Balance Of System (BOS) failure, such as block diodes, transformers, switches, etc. The ratio of failure causes of PV systems in Taiwan is shown in Fig. 8.

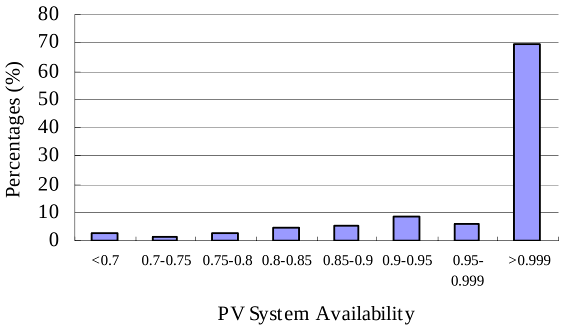


Fig. 7 The distribution of PV system availabilities in Taiwan

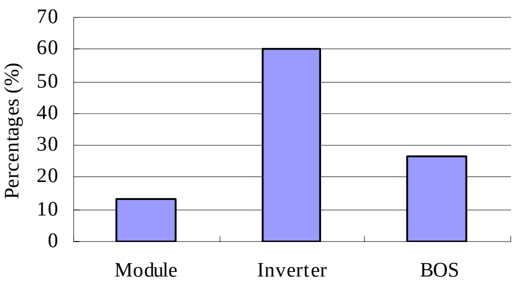


Fig. 8 The ratio of failure causes of PV systems in Taiwan

Fig. 9 shows the distribution of average repair time MTTR for the 62 PV systems with event happened from 2006 to 2008. The average MTTR is 65 days. It is indicated that for a failure event, average time 65 days are required to restore the PV system to normal operation.

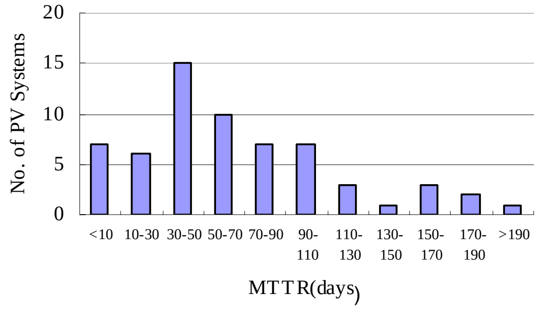


Fig. 9 The distribution of average repair time MTTR for the 62 PV systems with event happened

Fig. 10 shows the distribution of average failure time MTTF for the 202 PV systems from 2006 to 2008. Within the 202 PV systems, 140 sets have not encountered any failure event but 62 sets have. By using the MTTR and availability information described above, the MTTF can be estimated as 3.96 years. It is indicated that the PV system will have an event after normal operating for 3.96 years.

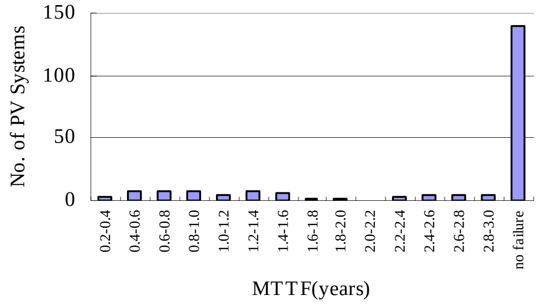


Fig. 10 The distribution of average failure time MTTF for the 202 PV systems

*D. Relationship between PR value and availability of PV systems*

Fig. 11 shows the relationship between PR value and availability of 202 PV systems in Taiwan. Roughly speaking, there is a linear relationship between PR value and system availability. In other words, that is low PR value may happen for low availability (high failure rate). However, in Fig. 11, under the condition that system availability equals to 1, the PR values still distribute within a big range from 0.43 to 1.0. It is indicated that except for availability, inverter efficiency, shading condition, array orientation and module temperature will have an impact on the PR value.

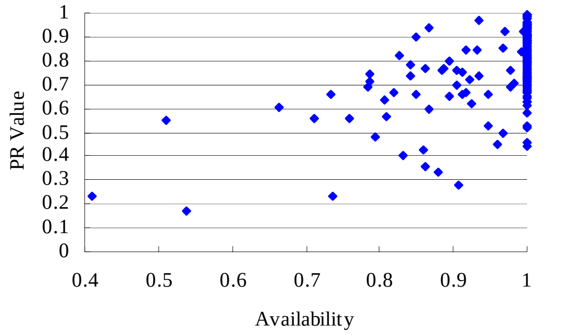


Fig. 11 The relationship between PR value and availability of 202 PV systems

### *E. Compare with other countries*

IEA performance database includes performance and availability technical data of 505 PV plants with a capacity more than 13.5 MW. The formats of data collection and display are defined according to the international standard [6]. The involved countries include Germany, Japan, Italy and Switzerland, etc. TABLE III shows the PR values and availabilities of PV systems in these countries [7], including those of Taiwan. From TABLE III, it can be seen that the PR value in Taiwan is slightly higher than that of other countries due to newer system equipments. The availability of PV systems in Taiwan approximately equals to that of other countries. Improvement is required in the future. If the availability of PV systems can be improved, PR value should be higher.

TABLE III
THE PR VALUES AND AVAILABILITIES OF VARIOUS COUNTRIES

| Country | No. of PV systems | Measured period | PR value | Availability(%) |
|---|---|---|---|---|
| Germany | 111 | 1991-2002 | 0.67 | 94.6-95.9 |
| Italy | 34 | 1991-2002 | 0.65 | 94.6-95.9 |
| Japan | 87 | 1995-2002 | 0.73 | NA |
| Switzerland | 64 | 1989-2001 | 0.69 | 94.6-95.9 |
| Taiwan | 202 | 2006-2008 | 0.74 | 95.7 |

Table IV shows the MTTFs and MTTRs for the PV systems in Japan, USA and Taiwan [8-9]. From TABLE IV, it can be seen that the average repair time MTTR has a big gap between various countries. On one hand, if PV plants installed with real-time monitoring system, the MTTR is shorter. On the other hand, without real-time monitoring system, the MTTR is longer. They may differ with more than 60 times. It is indicated that it will be helpful for improving MTTR and availability by installing real-time monitoring system. If the MTTR of Taiwan's system can be improved to 3.3 days like Japan's system, the availability of PV systems in Taiwan will be risen to 99.77%.

TABLE IV
THE MTTFS AND MTTRS OF PV SYSTEMS IN JAPAN, USA AND TAIWAN

| Country | No. of PVPV systems | Measured period | Is real-time monitoring? | MTTF(year) | MTTR(day) |
|---|---|---|---|---|---|
| Japan | 78 | 2004-2005 | Yes | NA | 3.3 |
| USA (EPA) | 15 | 1993-1996 | Yes | 1.2 | 19 |
| USA (SMUD) | 332 | 1993-1995 | No | 7-16 | 75-210 |
| Taiwan | 202 | 2006-2008 | No | 3.96 | 65 |

## V. CONCLUSION

In this article, 202 grid-connected PV system operational data for three years, such as monthly final energy yields and failure records, collected by ITRI in Taiwan is used to analyze the performance and system availability. The average final system yield is 2.61 hours, the average PR value is 0.74, the average MTTF is 3.96 years, average MTTR is 65 days and the average availability is 95.7%. Roughly speaking the lower the PR values, the higher the failure rates. Hence, installing real-time monitoring systems for PV plants are suggested to improve the system availability and PR value. It can help to find the system failure event earlier and then repair the systems more quickly. In the further study, the monitoring systems can be installed in many representative locations to obtain more accurate and more complete electrical data.

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