INTERNATIONAL ENERGY AGENCY TASK II DATABASE ON PHOTOVOLTAIC POWER SYSTEMS: STATISTICAL AND ANALYTICAL EVALUATION OF PV OPERATIONAL DATA


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ABSTRACT: As a part of the International Energy Agency (IEA) Photovoltaic Power Systems Co-operative Programme (PVPS), Task II, the above mentioned participants are collecting and analysing operational data of photovoltaic plants in various system techniques (grid-connected, stand-alone, hybrid) located all over the world. The objective of this joint project is to provide PV experts and other target groups with suitable information on the operational performance of PV systems and their subsystems. The developed IEA database is designed to gather and standardise the operational data of PV systems applied to various uses in order to achieve an assessment of their performance on the same base. Detailed system characteristics of existing PV plants as well as operating results of the monitored PV systems are stored in this database and made available to the users. The analysis allows comparisons between existing PV systems in different countries with different climatic conditions, PV plants using various system techniques and PV systems of different consumption behaviour.

KEYWORDS: Evaluation - 1: Performance - 2: Database - 3

1 INTRODUCTION

The objective of this joint project is to provide PV experts and other target groups with suitable information on the operational performance of PV systems and their subsystems. The participants of the International Energy Agency (IEA) Photovoltaic Power Systems Co-operative Programme (PVPS), Task II, are collecting and analysing operational data of photovoltaic plants in various system techniques (grid-connected, stand-alone, hybrid) located in IEA member countries and world-wide. The corresponding IEA PVPS Task II database is conceived to decentralised computer aided usage. Detailed system characteristics of existing PV plants as well as operating results of the monitored PV systems are stored in this database and made available to the users.

A first target group are consultancies that will be supported in planning PV projects. Furthermore, they will be given information on manufacturers of subsystems as well as on typical energy data. Secondly, the database can be used to check the operational behaviour of existing PV plants in detail (operators, industry) and to prove the readiness for use and efficiency of PV technology in general (utilities, decision-makers). Thirdly, the database can be implemented as a tool in training courses for people who want to improve their knowledge in PV system technique (utilities, planning and installing companies).

2 DATABASE

The IEA PVPS Task II database contains data of a large number of existing photovoltaic plants world-wide, which are equipped with data acquisition devices. Today, system characteristics of 260 monitored PV plants with an installed capacity of 12 MWp are available, stored in 170 data fields. Besides general information, these files contain details concerning the plants themselves (e.g. grid-connected, stand-alone, or hybrid system), their installation (integrated into a roof or facade, mounted onto a frame, etc.), their subsystems, and economic data. Monthly recorded data concerning meteorology (irradiation and temperature) and energy yield (DC output of the PV array, AC output of the inverter, AC power consumption, AC energy drawn from or fed into the public grid, etc.) are used to determine energy balances (final yields, system losses, capture losses), performance ratios, the efficiencies of the systems or subsystems, and the solar fractions. The availability of the PV plant (outage fraction) and the measuring devices (monitoring fraction) are permanently recorded. Data concerning costs include expenses for construction and operation of all components of the overall system, as well as for design and installation.

The set-up and the configuration of the decentralised PC database with the main work station at the ISFH have been finished to a large extent. An
3 OPERATIONAL PERFORMANCE

For the performance evaluation, the monitored and calculated data are exported from the IEA database. The data are analysed and the results are presented according to the guidelines defined by the CEC, Joint Research Centre, Document B [1].

The following derived parameters are used as system performance indices:

- Final system yield $Y_f$ [kWh/kWp*d]
- Reference yield $Y_R$ [kWh/kWp*d]
- Array capture losses $L_C$ [kWh/kWp*d]
- System losses $L_S$ [kWh/kWp*d]
- Performance Ratio $PR$ [-]
- Mean array efficiency $η_{A,mean}$ [-]
- Inverter efficiency $η_{inv}$ [-]
- Overall plant efficiency $η_{tot}$ [-]


Figure 1 shows a standard representation of the operational performance of a grid connected PV system, which can be displayed using the database „PVreport programme“. The database contains monitored data from 260 PV systems with an installed capacity of over 12 MWp. Grid connected PV systems are in majority with 70 to 75 %, while stand-alone systems are presented to a smaller extent.

3.1 Grid connected systems

Most of the monitoring data of grid connected PV systems in the IEA database have been gathered under various demonstration programmes in IEA member countries (e.g. Austrian roof-top programme, German „1000-roof-PV-programme“, Swiss demonstration programmes). This includes small PV systems in the range of 1 to 5 kWp for domestic use and demonstration, medium size systems with installed capacity between 10 and 100 kWp for various applications as well as large PV power plants of nominal power between 100 kWp and 3 MWp. The power range and number of systems differ from country to country. Switzerland supplied data from small PV systems up to power plants covering nominal powers from 1 to 560 kWp. German PV plants are predominately small systems in the range between 1 and 5 kWp. Japan offers a great variety of system configuration and size with nominal power of 2 to 750 kWp, while Italy supplied data of very large PV power systems with an installed capacity between 300 kWp and 3 MWp.

![Annual Final Yields and Performance Ratios](image)

Figure 2: Presentation of operational results from 140 grid connected PV systems in six IEA countries - system yields and performance ratios

Particularly complete statistics are available from 140 grid connected PV systems in six IEA countries. The yearly mean performance indices were determined and examined with respect to the country as their PV systems show certain typical characteristics (e.g. irradiation, power range). Figure 2 shows the mean annual system yield and performance ratios for each country, where system or component failures are not excluded in order to gain realistic values. Israel ranks best in mean final yield ($Y_f = 3.5$ kWp/kWh*d), Germany and the Netherlands have lowest $Y_f$ values ($Y_f = 1.8$ kWp/kWh*d). This difference in the order of factor two is quite significant, but can generally be explained by the difference in mean irradiation ($H = 6.6$ kWh/m2*d) for Israel and ($H = 2.6$ kWh/m2*d) for Germany.
kWh/m²*d) for the Netherlands. The annual performance ratios may differ within one country (for Switzerland: PR = 0.56 to 0.82), but the mean performance of all systems gives a good indication. Switzerland (20 systems, 2 years) and the Netherlands (7 systems, 2 years) show best results with mean PR values of 0.69 followed by Germany (90 systems, 2 years) with mean performance ratio of 0.67. Italy (3 systems) has lowest mean PR of 0.43, but a relatively small sample is considered.

The mean component and overall PV system efficiencies are presented in Figure 3. Mean annual array efficiencies range from 0.085 (Austria, 10 systems, 2 years) to 0.13 (Italy, 3 systems). An examination of the mean array efficiency for all projects (140 grid connected PV systems) with respect to time shows that the module efficiency is clearly improving. In the past years, manufacturers have supplied PV modules of higher efficiencies with realistic ratings.

The mean inverter efficiency covers a broad range from $\eta_{inv} = 0.73$ for Japan (14 systems, 1 year) to $\eta_{inv} = 0.90$ for Switzerland (20 systems, 2 years), which may partly explain their performance values of PR = 0.64 and PR = 0.69 respectively. A clear improvement of inverter efficiency with time is noted as a number of high efficiency inverters have been developed for grid connected applications. Excellent yearly mean inverter efficiencies of $\eta_{inv}$ greater than 0.95 were found in large PV power systems with an installed capacity of 100 kWp and above. Thus, the mean overall plant efficiency for grid connected PV systems is also improving with time, demonstrated in the latest PV projects with overall system efficiencies greater than 0.1.

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Regarding the load, 87 % of the requested yearly energy has been supplied by PV energy ($E_{PVuse} = 1.1$ kWh/d), 13% is needed from the back-up generator ($E_{BU} = 0.16$ kWh/d) as shown in Figure 5. Thus the system is undersized with respect to PV, but this hybrid-solution is a fine option to fulfil even increasing energy demand and achieves good performance ratios (PR = 0.48). In the case of a stand-alone system without back-up generator and having the same load profile, the performance of the system would drop down to about PR = 0.20.

Load evolution has to be considered as the owner needs to adapt his consumption behaviour to the PV system. From other experiences, loads are likely to increase in the first years after PV installation and eventually stabilise with time. For the systems under...
investigation, the load fluctuations were in the range between -15% to +15% with two exceptions [2]. Table I gives an overview of the results and presents mean annual final yield, array and capture losses, performance ratio, energy consumption, back-up energy and solar fraction for the eight French installations. The annual final yield range between $Y_f = 0.61 \text{ kWh/kWp*d}$ and $1.75 \text{ kWh/kWp*d}$ and the corresponding performance ratios between $PR = 0.16$ and $0.51$. For the installation with no back-up generator (see Table I, plants 2, 3 and 8), the capture losses are dominating and dramatically exceed the final yield, thus giving very low values of performance ratio.

The PV system output energy per year varies between $E_{pv,use} = 0.39$ and $2.42 \text{ kWh/d}$ depending on the energy consumption. $E_{pv,use}$ was used to calculate the solar fraction by: $F_S = E_{pv,use} / E_{load}$, where $E_{load}$ is the sum of the PV system output energy $E_{pv,use}$ and the back-up energy $E_{BU}$. The investigated PV systems achieved very high mean annual solar fractions of 87 to 100 %.

Both parameters performance ratio and solar fraction need to be considered for the system quality as the PR value of a stand-alone system is depending on the energy consumption behaviour. The parameter PR of a stand-alone system does not include the fact that solar energy is wasted depending on the system configuration and size of the components (e.g. battery).

### Table I: Comparison of eight French stand-alone installations - Performance and consumption parameters

<table>
<thead>
<tr>
<th>Plant</th>
<th>$Y_f$</th>
<th>$L_c$</th>
<th>$L_s$</th>
<th>PR</th>
<th>$E_{pv,use}$</th>
<th>$E_{BU}$</th>
<th>$F_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant 1</td>
<td>1.06</td>
<td>1.59</td>
<td>0.13</td>
<td>0.38</td>
<td>0.05</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>Plant 2</td>
<td>0.76</td>
<td>2.40</td>
<td>0.12</td>
<td>0.23</td>
<td>0.22</td>
<td>0.72</td>
<td>1.00</td>
</tr>
<tr>
<td>Plant 3</td>
<td>0.61</td>
<td>2.94</td>
<td>0.19</td>
<td>0.16</td>
<td>0.39</td>
<td>0.01</td>
<td>0.98</td>
</tr>
<tr>
<td>Plant 4</td>
<td>1.73</td>
<td>1.56</td>
<td>0.30</td>
<td>0.48</td>
<td>1.07</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>Plant 5</td>
<td>1.49</td>
<td>1.49</td>
<td>0.27</td>
<td>0.46</td>
<td>1.30</td>
<td>0.11</td>
<td>0.92</td>
</tr>
<tr>
<td>Plant 6</td>
<td>1.44</td>
<td>1.94</td>
<td>0.21</td>
<td>0.40</td>
<td>0.69</td>
<td>0.05</td>
<td>0.94</td>
</tr>
<tr>
<td>Plant 7</td>
<td>1.75</td>
<td>1.36</td>
<td>0.32</td>
<td>0.51</td>
<td>2.42</td>
<td>0.51</td>
<td>0.85</td>
</tr>
<tr>
<td>Plant 8</td>
<td>1.21</td>
<td>2.00</td>
<td>0.17</td>
<td>0.36</td>
<td>0.87</td>
<td>/</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### 4 CONCLUSIONS

The analysis of data from the IEA database led to increased understanding of the performance (expressed in terms of performance ratio) that were found for various applications and system configurations. From the performed evaluation, the following values of performance ratio (yearly mean) can be expected for the different system types:

- Grid connected PV systems: $PR = 0.6 - 0.8$
- Stand-alone PV systems without back-up: $PR = 0.1 - 0.4$
- Stand-alone system with back-up: $PR = 0.2 - 0.6$

For large, grid connected PV power plants with excellent inverter efficiency, the annual performance ratio may achieve values greater than $PR = 0.8$. As a first result, grid connected systems have generally improved in efficiency due to further improvements in component efficiency and optimised system design. The module efficiency is clearly improving and the manufacturer given rating of nominal power is closer to the monitored and realistic value. As high efficiency inverters have been developed for grid connected systems during the past years, the inverter efficiency is also tending to increase.

With stand-alone and stand-alone hybrid systems, the operational performance is not only depending on component efficiency but also on system design and consumption behaviour. If the consumption level is not well analysed, the oversized PV system results in very low performance ratio due to dominating capture losses, which are exceeding the system yield up to five times. The PV hybrid system with a back-up fraction of 15 to 25 % [2] gives the user a good option to fulfil his energy demand with high reliability and achieves good performance values with a lower size of PV system at the same time. Improvements in system design and system operation are possible by making use of the lessons learnt in careful system sizing, training of users, battery charge control and management of hybrid systems.

### REFERENCES
