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RELIABILITY OF GRID-CONNECTED PHOTOVOLTAIC SYSTEMS – THE LEARNING CURVE IN YIELD AND SYSTEM COST

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ABSTRACT: The scope of this paper is to give an overview of the system costs of 527 grid-connected PV systems from the data collected over a 18-month-period as part of the IEA PVPS Task 2 Economic Survey and operational performance of 461 grid-connected PV systems from the IEA PVPS Database. The datasets analysed are mainly from small residential grid-connected PV systems and also from some larger grid-connected PV systems from 11 countries for the cost data and from 17 countries for the operational data. They include freestanding, roof top and façade integrated systems. The PV plants investigated were built between 1991 and 2006. The monitored data from the 461 PV systems comprises datasets from 1 544 operational years. Analysis of the data available shows a trend towards lower system cost and a higher performance ratio (PR) over time. This paper is a summary of the IEA PVPS Task 2 Report T2-06-2007 [3].

Keywords: Grid-connected, Analysis, System performance, Cost reduction.

1 OVERVIEW

This paper contains two separate sections, the turnkey cost analyses of PV systems from data obtained from the **Task 2 Cost over Time** survey and the analysis of operational data taken from the **Task 2 Performance Database**. Table 1 shows a list of the data used for the evaluation.

Table 1: Overview of data used for the analysis.

		Systems	Years
System data			
System cost	$/W	527	--
Nominal module efficiency	η_{stc}	461	--
Monitored data			
Yield data	Y_f	461	1 544
Performance data	PR	461	1 544
Inverter data	η_{inv}	331	1 066
Array data	η_{arr}	218	570
Outage > 0	O	135	640

A comprehensive analysis of all the data in this economic and performance survey is published in the IEA PVPS Task 2 Report T2-06:2007. [3]. The Task 2 report also contains case studies from eight Task 2 member countries on system cost, yield over time, performance over time and PV plant failure.

2 COST OVER TIME SURVEY

From June 2005 until December 2006 the interactive database was active for the PV community to enter system-, economic- and operational data of PV systems. The data were entered mainly by PV plant owners/operators. Some data were also supplied in bulk by Task 2 members.

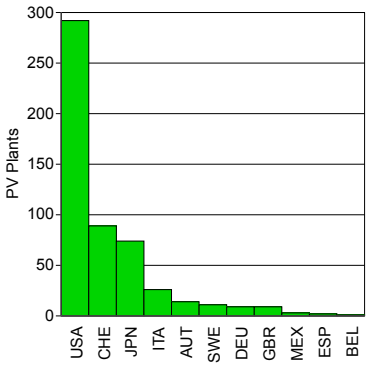

Figure 1, Datasets of economical data by country.

In total data from 774 PV systems was collected over an eighteen month period. Of the 774 datasets collected, 527 sets from PV systems from 11 countries contained useful economic data for this evaluation. In figure 1 all the 527 systems are grouped by country.

In table 2 the number of entries and total and average nominal power per country is shown. The number of systems per country ranges from 1 for Belgium to 292 for the United States. The total nominal power of all the 527 systems is 11 063 kW.

Table 2: Overview of all the economical data used.

Country	ISO country code	Total systems	Total nominal power [kW]	Average nominal power [kW]
United States	USA	292	1 528.8	5.2
Switzerland	CHE	88	3 026.4	34.4
Japan	JPN	74	1 295.0	17.5
Italy	ITA	24	4 508.8	187.9
Austria	AUT	14	111.1	7.9
Sweden	SWE	11	287.5	26.1
Germany	DEU	9	101.6	11.3
United Kingdom	GBR	9	183.3	20.4
Mexico	MEX	3	5.2	1.7
Spain	ESP	2	10.8	5.4
Belgium	BEL	1	5.2	5.2
	11	527	11 063	21.0

Most of he 292 PV systems in the USA were built in the years 2003 to 2005 and 229 PV systems have a nominal power ranging from 1 to 10 kW.

Table 3: List for the typical use and mounting with number of systems for each section.

Typical use	Systems
Domestic	262
Power station	95
Other	64
Office	39
Appartments	24
Housing-Other	20
NA	10
Factory	9
Other Professional	2
Other Rural	1
Vacation house	1
	527

Mounting	Systems
NA	322
Rooftop	158
Free-standing	25
Facade	14
Other	7
Soundbarrier	1
	527

As shown in table 3, 262 of the 527 are domestic systems. The type of mounting was not reported in 322 cases. 158 roof mounted systems are on top of the list.

About 363 (69%) of the 527 systems are smaller than 10 kW (Figure 2) and the remaining 164 PV systems have a nominal power ranging from 10 to 2 970 kW.

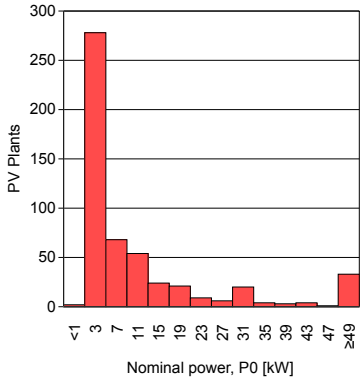

Figure 2: PV systems by nominal power.

2.1 Economic data

All the cost data were converted into 2005 prices and into USD. The tables used for this conversion were the OECD consumer price index (CPI), 2007 and the historical exchange rates (HExR), 2007.

In total 527 datasets containing valid economical data from 11 countries were used for this section. The year of construction of the PV plants ranges from 1992 to 2006. Figure 3 shows a histogram of the plant cost. 80% of the plants are in the 6 to 12 USD/W range.

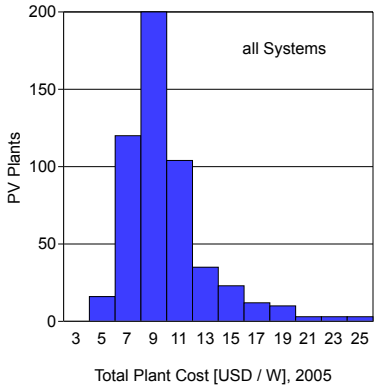

Figure 3: Plant cost.

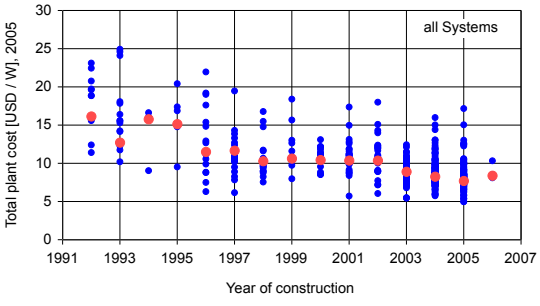

Figure 4: System cost over time, all data.

In figure 4 the plant costs over time are shown, including all the values and the mean value for each year from 1992 to 2006. In figure 5 the values for the United States were omitted. Both figures show a clear trend of a decrease in plant cost over time, from 16 USD/W in 1992 to 8 USD/W in 2006.

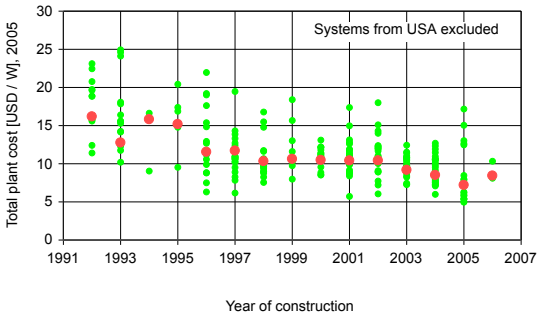

Figure 5: Cost over time, excluding data from USA.

3 IEA PVPS PERFORMANCE DATABASE

Task 2 set up the IEA PVPS Performance Database in 2000 and has maintained it up to the end of 2007. The latest edition of the database (2007) contains data from 505 PV systems with 1 648 years of operational data. Of the 505 PV systems built between 1983 to 2005, 445 systems or 88% are grid-connected. The plant and operational data were supplied by the Task 2 members for their respective countries. Data from past Task 2 members, Israel and the Netherlands, are also available in the database. Some non-members also supplied data.

3.1. The PV systems analysed

An additional 39 grid-connected PV systems with valid performance data from the economic survey were added to the 445 selected grid-connected PV systems from the IEA PVPS Database. For this report, only 461 grid-connected PV systems built between 1991 and 2006 with a total of 1 544 operational years are analysed (Table 4).

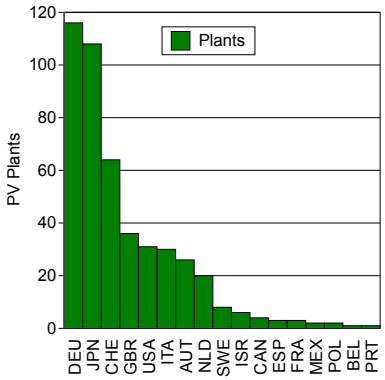

Figure 6: All 461 grid-connected PV system, grouped by country.

The entries for PV systems in Germany, Japan and Switzerland make up 63% of the systems, 74% of the operational years and 53% of the total nominal power (Table 4).

Table 4 Number of PV systems and nominal power per country.

Country	ISO country code	Total systems	Years of Data	Average years	Total nominal power [kW]	Average nominal power [kW]
Germany	DEU	116	442	3.8	1 618.0	13.9
Japan	JPN	108	355	3.3	2 095.4	19.4
Switzerland	CHE	64	341	5.3	2 848.1	44.5
United Kingdom	GBR	36	73	2.0	158.6	4.4
United States	USA	31	55	1.8	120.0	3.9
Italy	ITA	30	86	2.9	4 624.1	154.1
Austria	AUT	26	48	1.8	86.4	3.3
Netherlands	NLD	20	52	2.6	535.7	26.8
Sweden	SWE	8	29	3.6	107.2	13.4
Israel	ISR	6	9	1.5	6.2	1.0
Canada	CAN	4	26	6.5	20.9	5.2
France	FRA	3	6	2.0	32.9	11.0
Spain	ESP	3	6	2.0	52.8	17.6
Mexico	MEX	2	4	2.0	3.5	1.8
Poland	POL	2	6	3.0	1.8	0.9
Belgium	BEL	1	4	4.0	5.2	5.2
Portugal	PRT	1	2	2.0	5.0	5.0
	17	461	1 544	3.3	12 322	26.7

Table 4 shows the PV systems by typical use and type of mounting. Of the 461 systems 39% are domestic systems and 20% are power stations. 73% are roof top systems and 15% are free-standing.

Table 5: Typical use and mounting

Typical use	Systems	Average P0 [kW]
Domestic	179	3.98
Power station	91	96.92
Other	56	7.19
Office	42	32.30
Housing-Other	21	17.84
School	18	3.98
Apartments	14	4.26
Factory	12	25.40
NA	11	2.44
University	11	1.25
Other Professional	2	52.30
Vacation house	2	22.05
Hotel	1	20.20
Water pumping	1	10.37
	461	26.73

Mounting	Systems	Average P0 [kW]
Rooftop	338	14.14
Free-standing	70	86.91
Façade	28	15.56
Other	18	27.75
Soundbarrier	7	74.83
	461	26.73

Figures 18 to 20 show the distribution of the nominal power. Of the 461 PV systems 73% are smaller than 9.9 kW, 24% are in the range of 10 to 99 kW and 4% are larger than 100 kW.

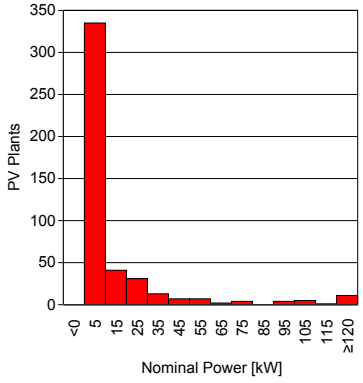

Figure 7: Distribution of the nominal power

3.2 Nominal module efficiency

The efficiency value of about 35% of the systems is around 11.5% to 12.5%. In figure 8 the nominal module efficiency is shown relative to year of construction for the 461 systems built from 1991 to 2005. The mean value of the crystalline cells for each year is also shown.

The overall trend is an increase from about 11.6% to 12.9% of the installed nominal module efficiency for the period from 1991 to 2005.

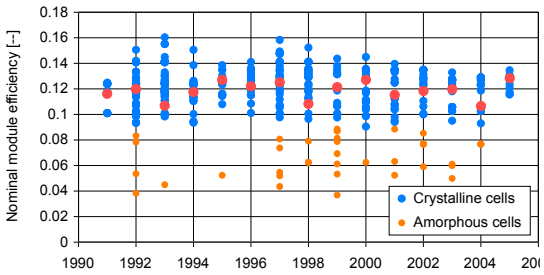

Figure 8: Nominal efficiency over time.

3.2 Yield

In this section the yield data from 461 grid-connected PV systems with a total of 1 544 operational years are shown in the figures 9 and 10. The final yield (Y_f) is the ratio of the energy produced by the PV plant to the nominal power (P_0). The final yield is a representative figure to compare similar PV systems in a specific geographic region.

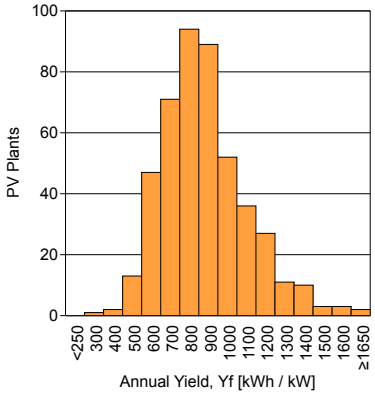

Figure 9: Annual yield.

The annual yield is dependent on the type of mounting, vertical on a façade or inclined on a roof and also on the location as shown in figure 10.

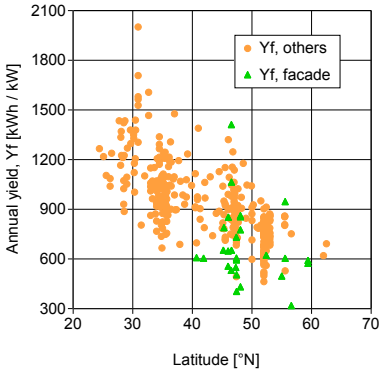

Figure 10: Annual final yield (Y_f) vs. northern latitude.

In figure 10 the final yield is shown relative to the geographical latitude of the northern hemisphere, ranging from locations in the south of Japan, the south of the United States, central Europe to Sweden.

3.3 Operational inverter efficiency

Figure 11 shows the operational inverter efficiency over time. Of the 461 systems used for this section of the report, 331 systems have monitored data for the inverter efficiency. The figure shows a rising mean efficiency over time.

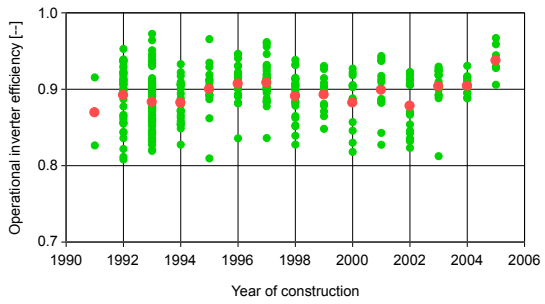

Figure 11: Annual operational inverter efficiency over time.

Figure 12 shows the distribution of the operational inverter efficiency. About 30% of the systems show an annual operational inverter efficiency between 89% and 91%.

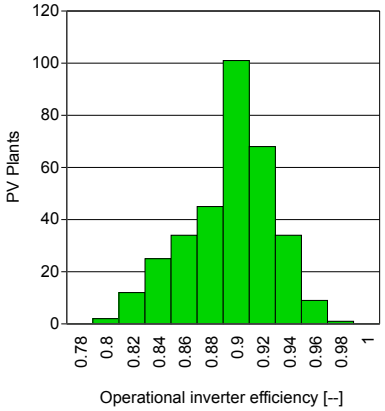

Figure 12: Distribution of the annual operational inverter efficiency.

3.4 Performance

The performance ratio (PR) is the ratio of the final yield (Y_f) to the reference yield (Y_r) for a given period. The value of the reference yield is identical to that of the irradiation on the PV array plane (H_i).

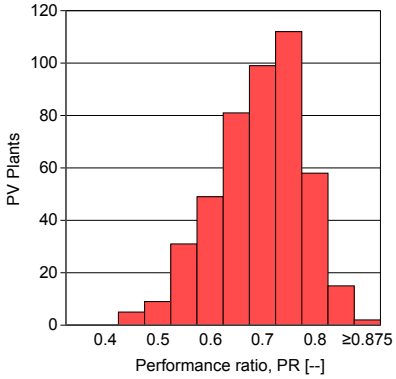

Figure 13: Distribution of performance ratio.

The performance ratio can be used to compare PV systems, independent of size, mounting and location. It expresses how much of the available solar energy is converted into electrical energy actually used.

From the survey performance data from 1991 to 2005 from 461 grid-connected PV systems with a total of 1 544 operational years are available. 62 % or 288 PV systems are located in Germany, Japan and Switzerland.

The values used in the figures 13 and 14 are the mean values for the whole monitoring period of the system. The monitoring period for each system varies from 1 to 14 years. Of the 461 PV systems represented in figure 13 about 48% are in the PR range from 0.725 to 0.775.

Figure 10 shows the performance over time for the 461 PV systems built between 1991 and 2005. The performance over time shows a trend of the mean annual PR from 0.64 in 1991 to 0.74 in 2005.

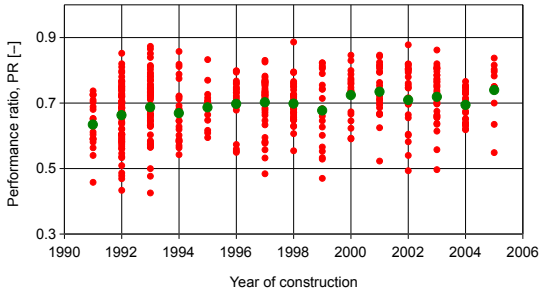

Figure 14: Performance ratio over time

3.4 Plant failure

The outage O is the downtime of a PV system. In figure 15, the reported outage is shown for each system (left scale) and as an average value for each year (right scale). Failures occur less often over time and for 10 out of 15 annual values, a decrease in the annual outage over time is apparent. The highest annual value is in 1995. The value of 0.045 means that the systems built in 1995 were not operating for 4.5% of the time.

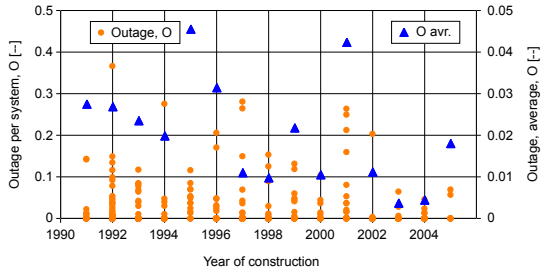

Figure 15, Reported outage (O) over time for all the systems and as an average value per year.

For quite number of systems, there is no reporting of any failures, even when the system has a lower than average performance ratio. Some of the datasets do not contain any outage data because the data are from globally monitored systems where the energy values are recorded manually on a monthly bases and the outage is not recorded. For only 135 PV Systems with a total of 640 operational years an outage > 0 was recorded.

4 CONCLUSIONS

4.1 Turnkey system cost

A significant finding of this report is a clear trend towards lower system cost over time from 16 USD/W in 1992 to 8 USD/W in 2005. The sample in this section of the report comprises 527 grid-connected PV systems from 11 countries built between 1992 and 2006. The sample also includes 292 systems in the USA. Most of the systems are domestic systems with a nominal power smaller than 10 kW.

4.2 Operational Performance

All 461 datasets selected for this part of the report are from grid-connected PV built between 1991 and 2005 from 17 countries. They are mainly domestic roof-top systems with a nominal power smaller than 10 kW. The mean annual performance ratio shows an upward trend from 0.64 in 1991 to 0.74 in 2005. The rise in the operational inverter efficiency, the decrease in the frequency and duration of outage and a more accurate module rating are contributing factors to the rise in the performance ratio over time.

A typical grid-connected PV system for the year 2005 shows an improvement of the overall plant efficiency of 29% compared to a system built in 1991. The overall plant efficiency in Table 5 is the product of the nominal module efficiency and the performance ratio.

Typical system	1991	2005	
Nominal module efficiency (ηA0)	11.6	12.9	%
Operational inverter efficiency (ηI)	89	94	%
Outage (O)	0.03	0.01	–
Performance ratio (PR)	0.64	0.74	–
Overall PV plant efficiency (ηtot)	7.4	9.5	%
Improvement	100	129	%

Table 6: Improvements over time

An important finding of this survey is that the performance ratio has increased over time, partly because of an increase in the nominal module efficiency. In the survey carried out, however, the reporting on outages and the type of failure is minimal. Accurate reporting on failures of PV systems as part of the monitoring would greatly contribute to the understanding of long-term behaviour of PV systems. Without such reporting one can only guess that the performance ratio has also increased because of an increased reliability of PV systems over time.

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