# Findings from Worldwide Studies of PV Module and System Performance

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## 1) Abstract

BP Solar has studied external data logging since 1998 on grid connected, maximum power point tracked or IV swept arrays including both BP Solar and competitors products at more than 100 sites world wide (Fig 1). Module Technologies studied include Laser Grooved Buried Grid, mono and multicrystalline Silicon; single, double and triple junction amorphous Si and CdTe from BP Solar and competitors.

System types studied include Comparative DC modules: IV sweep (Fig 2) or MPPT (Fig 3), also AC arrays such as Louvres (Fig 4) and retrofit Roofs (Fig 5).

All the data studied has come from real outdoor logging (Not indoor or theoretical models)

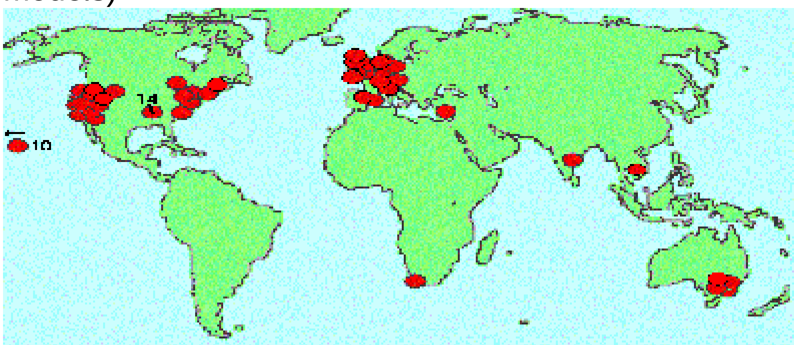

**Fig 1 :** Locations of some of the 100+ sites studied by BP Solar

**Fig 2 :** Comparative module testing using IV sweep scanners in Sydney

**Fig 3 :** Comparative module testing using MPP trackers at ISET in Germany

**Fig 4 :** BIPV Louvres in the UK

**Fig 5 :** Large Retrofit roof in Melbourne

**2) Measurements of systems more frequently than at hourly intervals**

Studies of weather data at measurement intervals more frequent than hourly in both Sydney (measured every minute 2002-2004) and ISET Kassel, Germany (taken every 15 seconds 2003) show that averaging data to hourly values distorts the actual energy versus irradiance curve to overestimate the low light level and underestimate the effect of high light levels. Both sites showed over 6% of Irradiant energy at over 1000W/m² with peak Irradiances seen at ~1350W/m² for short timescales.

Fig 6 shows a typical clear day in June in Kassel, Germany measured every 15 secs. The irradiance has a classic bell curve shape, the peak irradiance is 0.95 kW/m² and the Module temperature rise above ambient is around 25deg C. Fig 7 also shows the trace for a day a week later with intermittent cloud and sunshine, note the rapid changes in Irradiance (plotted every 15secs) from around 0.3kW/m² to 1.2kW/m². The fact that the irradiance spends some time well above the "clear sky" value obtained a few days earlier implies that when the sun is shining there is some increase in light level from reflections off bright clouds nearby. The module temperature rise is much lower than the clear day as the thermal mass of a module means it takes around 15 minutes to warm up after a step increase in irradiance.

This means that PV modules which react almost instantly in current with irradiance but have a time lag with their temperature can be running simultaneously at both much higher irradiances and at lower temperatures on intermittent cloudy days than simple hourly models would have suggested.

Fig 8 shows the proportion of Irradiant Energy (kWh/m²) at each Irradiance level for a commercially available stochastic hourly model vs 10-minute averaged data for a 30° tilted plane in 2003 in Kassel, Germany. All of the measured data shows much higher energy at high irradiances than the model predicts, this rises even further as the frequency of measurements increases. Averaging weather data over long time scales (such as hourly) will smooth out some high and low irradiances into mid range values whereas modules will react quickly to high light level peaks. Up to 1.35kW/m² has been measured for periods of under 1 minute – inverters and fuses need to be selected with these high peak values in mind.

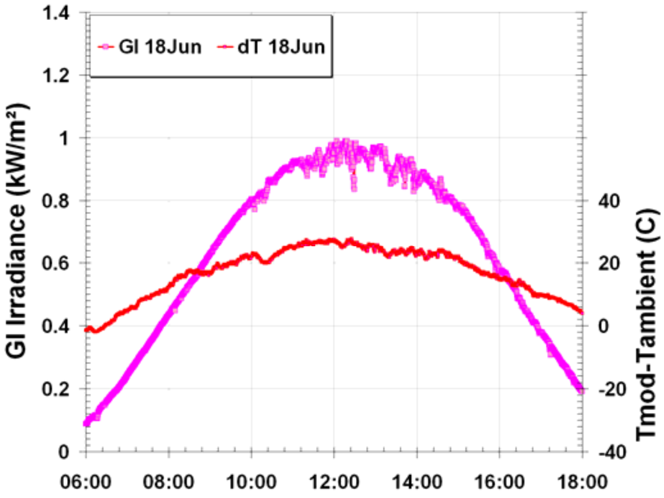


**Fig 6 :** Tilted plane Irradiance Gi and Module Temperature rise above ambient for a <u>clear day</u> (18 Jun 2003) in Kassel, Germany.

Peak Irradiance. 0.95kW/$m^2$
DeltaT ~ 25C at 12:00-13:00

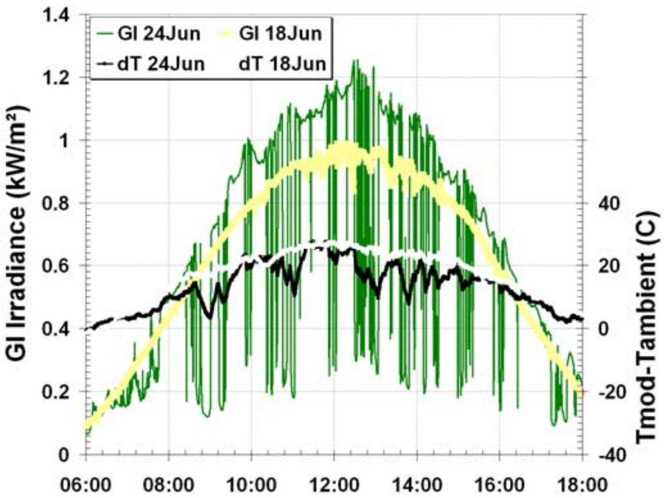


**Fig 7 :** Tilted plane Irradiance Gi and Module Temperature rise above ambient for a day <u>with intermittent cloud and sunshine</u> (24 Jun 2003) in Kassel, Germany.

Peak Irradiance ~ 1.2kW/$m^2$
DeltaT ~ 10 to 25C at 12:00-13:00

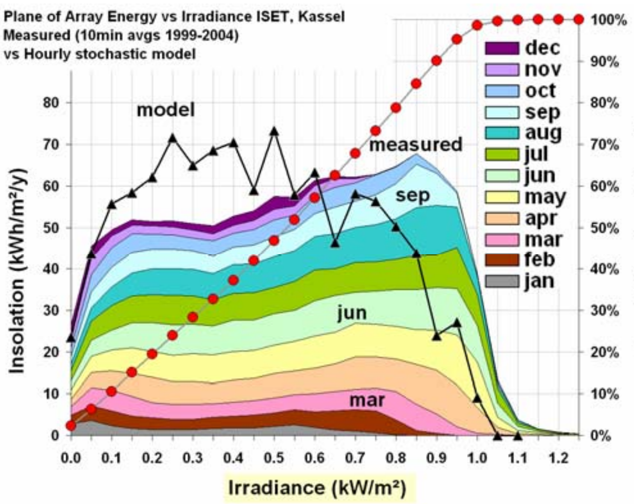


**Fig 8 :** Proportion of Irradiant Energy at each Irradiance level for a stochastic hourly model vs measured 10-minute averaged data for a 30° tilted plane in 2003 in Kassel, Germany

(This topic will be discussed further at the Barcelona PV Conference in a joint paper with ISET.)

**3) LGBC Solar Cell structure (BP Saturn Series 7)**

Fig 9 shows a stylised cross section through a Laser Grooved Buried Contact (LGBC) Saturn cell with

- 35 µm deep by 20 µm wide laser grooves filled with metal by plating to minimise series resistance

- selective emitter with a higher n++ doping under the fingers to minimise contact resistance
- lower n+ doping (100 ohms/[]) in the bulk for good blue light capture.

Fig 10 shows an equivalent circuit superimposed onto a not-to-scale cross-section of an LGBC cell (it is intended to identify where in the physical cell the equivalent circuit elements come from.)

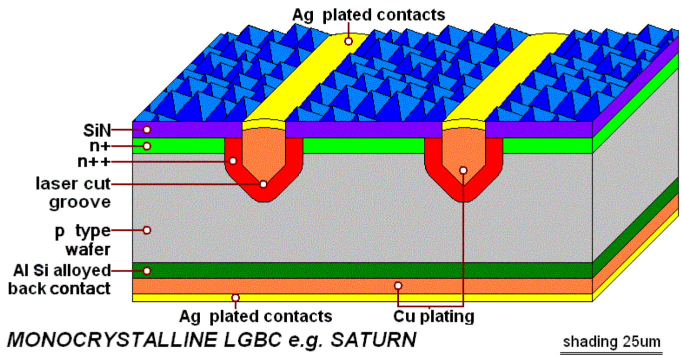


**Fig 9 :** A stylised cross section through a Laser grooved buried contact Saturn cell

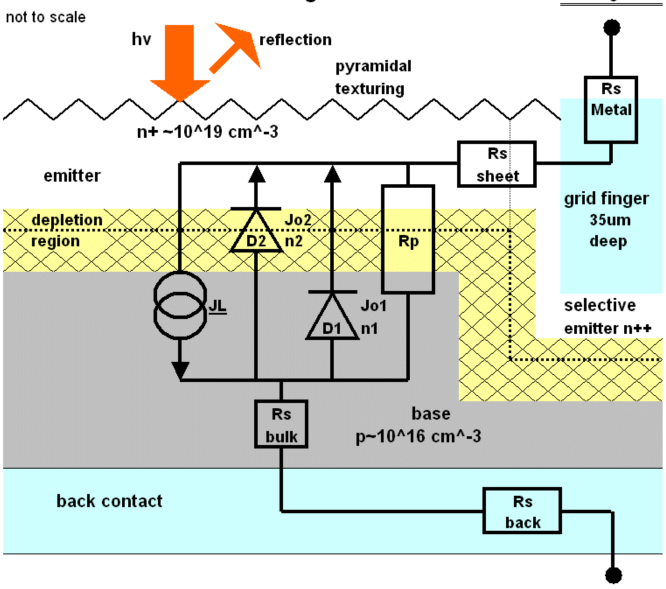


**Fig 10 :** Equivalent Circuit and Cross Section of a Laser Grooved Buried Contact Cell (Saturn)

## 4) Empirical formulae

Three formulae <1> to <3> have been developed and used to predict the module Yield (Y), optimum dc tracking voltage ($V_{DM} = V_{DC}/V_{MAX.STC}$) and Module temperature ($T_{MOD}$) from the measured Irradiance, Ambient temperature and wind speed in Fig 11.

Simple models of the AC system (Inverter and wiring loss, roof mounted temperatures and shading) have been used to prove good array performance or flag any downtime or other output limitations.

**<1>** $T_{MOD} = C'*T_{AM} + G_I*(A' + D'*WS) + E'$

**<2>** $V_{DM} = A''*LOG_{10}(G_I) + C''*T_{MOD} + D''*WS + E''$

**<3>** $Y = \Sigma_t G_I*(A+B*\Sigma_t G_I+C*T_{AM}+D*WS)-E$

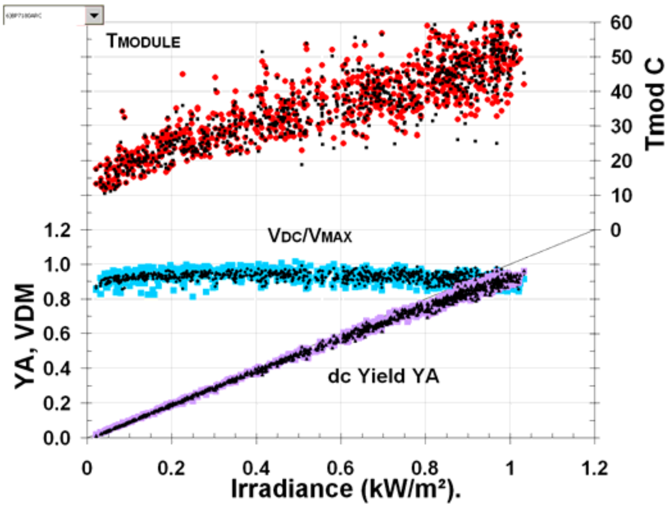


**Fig 11 :** Empirical fits vs Irradiance of $T_{MODULE}$, $V_{DM}$ and dc Yield for a BP 7180 measured in Australia.

### 5) AC Yield limitations

There are many loss mechanisms that can affect the measured system PR (only the first 4 in the list below are related to the module technology, all of the others are random or dependent on BOS performance):-

Module Technology Dependent

- Actual / Nameplate Pmax
- Stability (particularly Thin Film), pre stabilisation, LID
- High Module Temperature effects
- Module Mismatch

Random or BOS dependent

- Downtime (Random? WORSE IN SUMMER )
- Mistracking of array DC voltage, (transient or steady state)
- Wiring $I^2R$ Loss
- Shading : obstacle, horizon, self or row-to-row
- BOS Inverters : Low light level performance, saturation, turn on, (in)efficiency
- Dirt
- Snow
- Underperforming strings on large systems bring down average

A model has been developed to predict 15 different AC losses and compared with real systems. Input details of array spacing and 3 dimensional obstacle geometry have been used to estimate shading, Thermal models and TMY snow data have been used to study these effects. Fig 12 shows likely ranges for each of the losses.

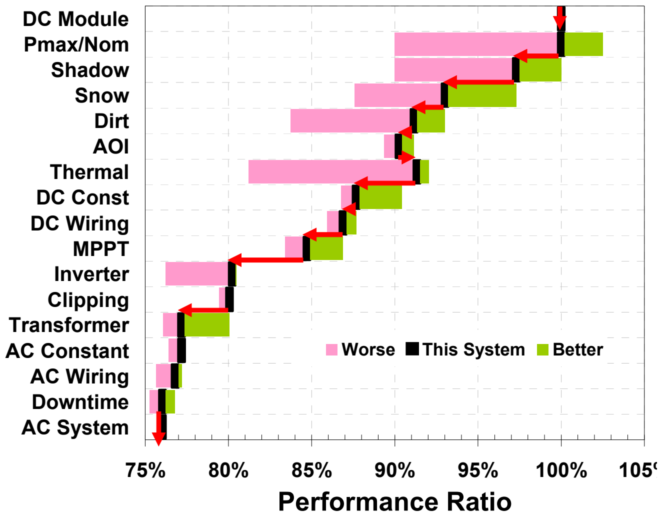


**Fig 12 :** Losses at each stage for a system in New York showing an expected performance ratio of 76% for this site

Figure 13 shows the actual vs predicted performance for a string in an array on a roof in the UK using the equations and parameters from section 3. It clearly shows very poor array performance around the middle of the day ($Y << Y_{CALC}$) due to the voltage tracking $V_{DM}$ being too high. On investigation it was found that after installation and commissioning the cooling fans to the inverter on the string had failed and the inverter was preventing itself from overheating by deliberately raising its dc voltage to reduce the input power. Late in the afternoon when the irradiance was lower together with the input power, the voltage tracking went back to more normal values. After the cooling fan had been repaired the string went back to performing well, the measured and predicted traces then matched very closely

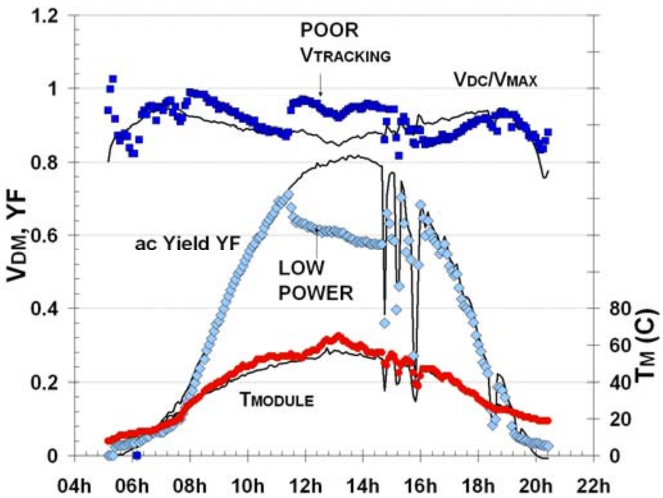


**Fig 13 :** Empirical predictions for $T_{MODULE}$, $V_{DM}$ and dc Yield to a BP 585 Array measured in the UK. Deviations of low power due to over tracking voltage enabled fault finding.

## 6) Outdoor conditions

Real outdoor dc module performance has been measured and modules of different technologies characterised against meteorological and physical parameters such as irradiance, clearness index kT, air mass (from solar height), angle of incidence and direct/global irradiance fraction.

Figure 14 shows how the $I_{DN}$ of a Saturn 585 module varied at ISET for the whole of 2003. 18000 measurements were made that year (every 10 minutes) and the graphs show the $I_{DN}$ vs irradiance, $T_{MOD}$, wind speed, diffuse fraction Gd/G0, clearness index kTh and angle of incidence.

All six of the graphs show very flat current collection meaning that the module's performance is optimised under all irradiance conditions. If a module were to be optimised for one irradiance condition then it would be less than optimum at all other irradiances. The highest energy (kWh) out for a module is where the efficiency under all conditions is as high as possible.

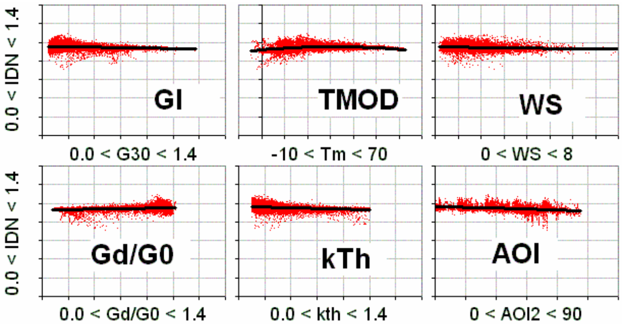


**Fig 14 :** Saturn $I_{DN}$ (=$I_{DC}/I_{MAX.STC}/G_I$) versus GI, $T_{MODULE}$, Wind speed WS, diffuse fraction Gd/Go, clearness index kTh and Angle of Incidence AOI showing flat, optimised performance

The ratio of highest to lowest measured Module efficiencies is over 3:1 (fig 15) which shows in the kWh/m² produced varying by this ratio between the highest Mono Si and lowest Amorphous Si technologies.

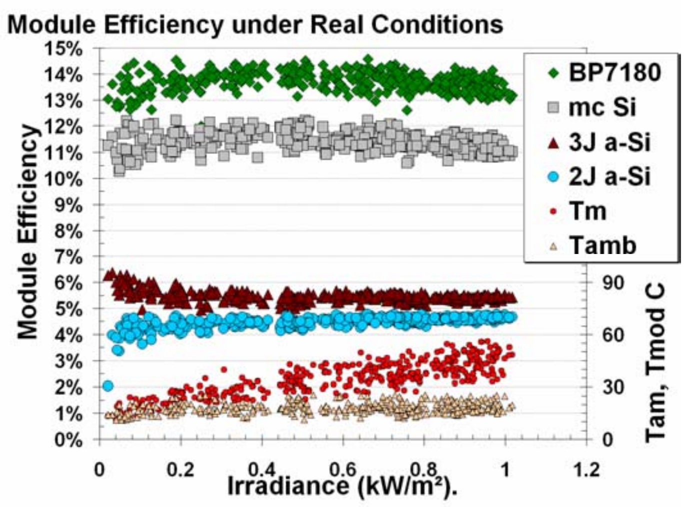


**Fig 15 :** Module efficiency vs Irradiance under real conditions ($T_{MODULE}$ 20-50C) in Sydney for a BP 7180 versus mc-Si, 2J a-Si and 3J a-Si from competitors

### 7) kWh/kWp predictions

Some commercially available Sizing programs use Markov transition matrices to generate hourly series of weather data. They then multiply the performance of the PV vs Irradiance and Temperature each hour and finally derate by a best guess of the BOS losses. (Fig 8 already showed how the irradiance data for Germany was wrong), Fig 16 shows how the measured performance of Saturn modules is much better compared with what is in the model's module database. Fig 15 showed the module's performance under real world conditions – in the field modules are generally hotter at higher irradiances and cooler at lower giving a flatter efficiency vs irradiance curve under operating conditions.

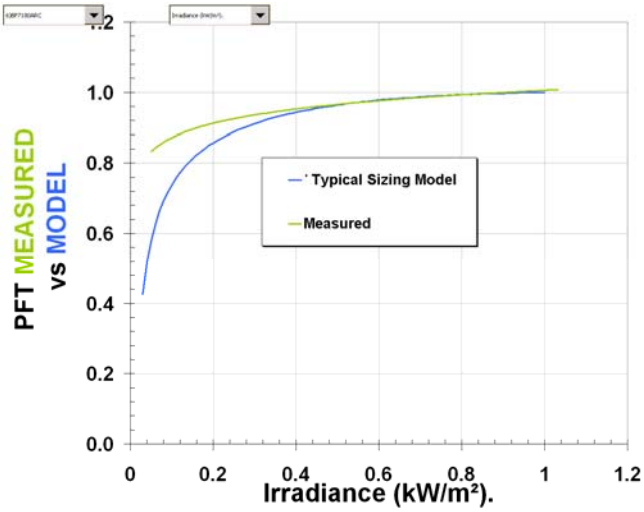


**Fig 16 :** The Performance factor corrected to 25C for a BP 7180 is much better than that used in a commercially available Sizing program's model.

**8) Conclusions**

- BP Solar has studied dc and ac modules and arrays at over 100 sites world wide.
- Averaging underestimates the importance of high light levels.
- Empirical equations can characterise dc modules and determine the optimum performance of arrays.
- A model has been developed to predict losses due to effects like snow, shading, inverter and wiring loss.
- Modules like the BP7180 having REAL POWER have been seen to have good flat performance under all conditions.
- Over 3:1 variation is seen between the highest and the lowest Module efficiencies.

**9) References**

More than 50 scientific papers (including those listed below) by BP Solar staff are available at the following website **http://www.bpsolar.com/techpubs**

**10) Acknowledgements**

ISET, Kassel, Germany http://www.pvtestlab.de

Numerous BP Solar staff in Frederick, Hamburg, Sunbury, Madrid, Bangalore and Sydney