MEASUREMENT OF PV MAXIMUM POWER POINT TRACKING PERFORMANCE

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ABSTRACT: Methods to measure the accuracy, error, and efficiency of maximum power point trackers (MPPT) have been identified and are presented in a schematic way, together with definitions of terms and calculations. These methods are the result of a review on how international institutes and private industries are determining the MPPT accuracy and efficiency. The intention of this paper is to invite discussion, and to stimulate other experts to contribute and to further refine the terms and procedures, as it is intended to generate an IEC-standard.

Keywords: MPPT - 1 : accuracy - 2 : efficiency - 3 : error - 4 : measure -5 : inverter - 6

1. INTRODUCTION

Inverter efficiencies typically declared are calculated as the fraction of AC output divided by DC input power. Inverter manufacturers and system installers assume that the inverters are normally working at the maximum power point (MPP) of the I-V curve of the PV array.

In practice, there are a number of factors which cause the actual operating point to vary from the true MPP. For example, devices that use search algorithms to find the MPP have to move constantly around this optimal point thus operating the array off of MPP for some period of time. Search algorithms use finite time and voltage or current steps that may cause some error.

These MPPT inaccuracies conspire to reduce the conversion efficiency of the PV array, and therefore, the entire system.

MPPT performance is important to system designers who are guaranteeing a certain system performance and need to know all of the system losses as well as to system operators who want to ensure that their system is operating per its specifications. Thus an inverter or separate MPPT certification should include MPPT performance.

When pressed, inverter manufacturers may claim an MPPT accuracy or efficiency, but this value is likely based on the resolution of the MPPT search algorithm, not on a measured performance. Appropriate methods for determining MPPT performance - both for certification purposes and for field verification - need to be defined, and, along with them, the terms and calculations to be used.

1.1. MPPT Algorithms

Maximum power point tracking (MPPT) is performed by some battery charge controllers and by most grid connected PV inverters. The principle is to adjust the actual operating voltage V (or current I) of the PV array so that the actual power P approaches the optimum value P_{MAX} as closely as possible (see figure 1).

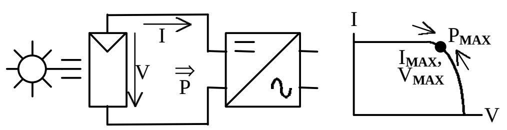


Figure 1: Maximum Power Point Tracking Principle

Many different ways exist to track the MPP which can be classified as either direct or indirect methods (see table 1). Direct methods include algorithms that use measured DC input current and voltage or AC output power values, and, by varying the PV array operational points, determine the actual MPP. Adjustment of MPP may occur continuously or intermittent, and algorithms may well or not include artificial MPP search movements.

Indirect methods are those which use an outside signal to estimate the MPP. Such outside signals may be given by measuring the irradiance, the module temperature, the short circuit current, or the open circuit voltage of a reference solar cell. A set of physical parameters has to be given, and the MPP setpoint is derived from the monitored signal.

Table 1: Overview: MPP tracking algorithms

Maximum Power Point Tracking Algorithms	
direct, controlled maximum through:	**indirect, derived set-point on basis of:**
maximise power $P = I \cdot V \rightarrow \max$ make derivative zero ${}^{dP}/_{dV} \rightarrow 0$, ${}^{dP}/_{dI} \rightarrow 0$ make quotient sum zero ${}^{V}/_{I} + {}^{dV}/_{dI} \rightarrow 0$	design parameters operational parameters system characteristics

1.2. MPPT Accuracy, Error, and Efficiency

Static and dynamic factors influencing MPPT behaviour include:

- power (irradiance level),
- voltage (temperature; layout including well- or mismatched PV and MPPT voltage ranges),
- fluctuations (clouds),
- PV technology (I-V curve shape)
- need (battery state of charge, in case of charge controller with MPPT).

Three terms can be used to describe how well an MPPT performs. They are functions of time (even under static conditions, due to MPPT search movements) and of additional parameters.

Accuracy (static and dynamic) indicates how close to MPP the MPPT operates the PV array and can be defined as a percentage of I_{MAX}, V_{MAX}, or P_{MAX}:

$$a_{MPPT.X} = X / X_{MAX}$$

$$\text{with} \quad X = I, V, \text{or } P$$

Efficiency indicates the ratio of actual to available PV array power (a particular case of accuracy) or energy [1]:

$$\eta_{MPPT.P} = P / P_{MAX}$$

$$\eta_{MPPT.E} = E / E_{MAX} \qquad \text{(see chapter 1.2.1.)}$$

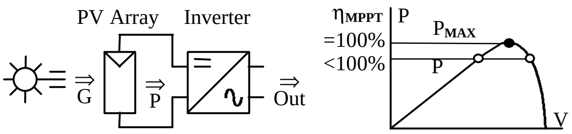
Error (static and dynamic) indicates the absolute or relative difference between actual and MPP values of voltage, current or power:

$$\varepsilon_{MPPT.X} = X - X_{MAX} \qquad \text{(absolute)}$$

$$\text{or} \quad X / X_{MAX} - 1 \qquad \text{(relative)}$$

$$\text{with} \quad X = I, V, \text{or } P$$

Accuracy and efficiency are essentially the same, however, efficiency, $\eta_{MPPT.P}$, can be used to 'correct' the inverter's conversion efficiency as shown in figure 2. Since the MPPT operates the PV array as a constant voltage or constant current source, voltage or current error better describes what the MPPT is doing. Also, voltage or current error for a given MPPT varies only as a function of IMAX and VMAX whereas efficiency is additionally a function of the PV array I-V curve shape (fill factor).



$$\eta_{TOTAL} = \eta_{PV} \cdot \eta_{MPPT.P} \cdot \eta_{INV}$$

$$\eta_{TOTAL} = \frac{P_{MAX}[W]}{G[W/m^2] \cdot A[m^2]} \cdot \frac{P[W]}{P_{MAX}[W]} \cdot \frac{Out[W]}{P[W]}$$

Figure 2: Efficiencies of MPPT and Power Conversion

1.2.1. Instantaneous vs. Integral Assessment

The MPPT's influence on the PV system performance depends both on its static performance - how closely it operates to a fixed MPP - and its dynamic performance - how well it responds to changes in MPP. The impact of static and dynamic effects can be accounted for using the following terms, calculating integrals from t = 0 to T_M :

MPPT Energetic Efficiency:

$$\eta_{MPPT.E} = E / E_{MAX} \qquad (\leq 1)$$
$$= \int_0^{Tm} P(t)\, dt \;/\; \int_0^{Tm} P_{MAX}(t)\, dt$$

MPPT Energetic Error (i.e. MPPT Energetic Loss):

$$\varepsilon_{MPPT.E} = E / E_{MAX} - 1 \qquad (\leq 0 \text{, indicates loss})$$
$$= \int_0^{Tm} P(t)\, dt \;/\; \int_0^{Tm} P_{MAX}(t)\, dt - 1$$

MPPT Average Efficiency:

$$\eta_{MPPT.A} = {}^{1}/_{Tm} \cdot \int_0^{Tm} \eta_{MPPT.P}(t) \cdot dt$$
$$= {}^{1}/_{Tm} \cdot \int_0^{Tm} P(t) / P_{MAX}(t)\, dt$$

The energetic performance is correctly expressed by the MPPT energetic efficiency $\eta_{MPPT.E}$, whereas the MPPT average efficiency $\eta_{MPPT.A}$, i.e. the average of the MPPT power efficiency $\eta_{MPPT.P}$, is equally weighted over time, regardless of high or low irradiance and power level P(t).

1.3. MPPT Assessment and Testing Methods Overview

Measuring MPPT behaviour has its complication, since two devices and their interaction are involved in the measurement - the PV array and the MPPT. The actual operating voltage and current of the PV array are readily measured but, it is not easy to determine V_{MAX} and I_{MAX} which vary with irradiance, temperature, spectrum and other conditions. Also, some inverters attempt to maximise the AC output rather than the DC input (PV array) power. This approach may result in operating the PV array off of MPP slightly but increasing the inverter efficiency such that the total sun light to AC efficiency is optimised.

Table 2 gives an overview of the identified methods to measure MPPT performance, which are divided into laboratory (indoor) and field (outdoor) measurements.

Table 2: Overview: MPPT Measurement Methods

MPPT Measurement Methods	
Laboratory (Indoor)	**Field (Outdoor)**
assessment under static conditions	switching between MPPT and I-V tracer
assessment under dynamic conditions	using a calibrated reference module
assessment of energetic efficiency	sampling MPPT input at high speed
	using manual mode to obtain I-V curve
further tests	analysing monitoring data

2. LABORATORY MEASUREMENTS (INDOOR)

To perform reproducible laboratory measurements, a PV array simulator is necessary that generates DC power with the I-V curve characteristic of a PV array. The exact simulation of such an I-V characteristic requires either a sophisticated control device or a network of diodes and resistors capable of handling large amounts of power. The simulator must be able to simulate an array under a variety of conditions (including different fill factors signifying different cell technologies) with satisfactory static accuracy as well as dynamic small-signal and large-variation response to high frequencies. The simulator must not interact with the MPPT in a way that is significantly different from a PV array.

2.1. Assessment of Static MPPT Performance

The purpose of this test is to measure the MPPT errors in voltage $\varepsilon_{MPPT.V}$, current $\varepsilon_{MPPT.I}$, and power $\varepsilon_{MPPT.P}$, under static conditions and as functions of important parameters.

Resulting plots display the MPPT errors as functions of V_{MAX} and P_{MAX}.

The principle of MPPT performance measurements is quite straight-forward (see figure 3).

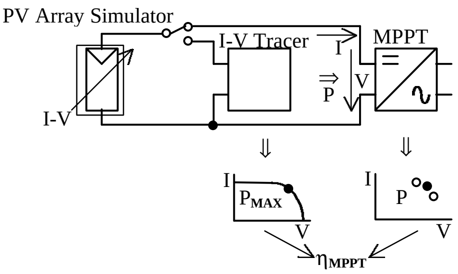


Figure 3: Static laboratory measurements

The MPPT is connected to the PV array simulator and the measured DC energy (or average current or voltage) over a certain measuring time T_M (e.g. a few seconds up to a few minutes) $\int_0^{Tm} P(t)\,dt$ is compared to the expected DC energy $P_{MAX} \cdot T_M$ (or I_{MAX} or V_{MAX}) which should have been extracted from the device if the MPPT had operated exactly in the MPP.

The PV array simulator should have reproducible performance, so that V_{MAX} and I_{MAX} can be measured easily. As the MPPT continuously moves around the MPP, taking only one pair of I and V values, or the average of all I and all V values, is not sufficient and reduces the measurement accuracy somewhat. Transient phenomena should have decayed before starting to measure, and $\eta_{MPPT.E}$ should be calculated on the basis of multiple samples within the measurement period T_M. Alternatively, $\varepsilon_{MPPT.V}$ or $\varepsilon_{MPPT.I}$ can be calculated for each sample and averaged over the period T_M.

Laboratory measurements with PV array simulators have the advantages of being convenient, fast, and reproducible. However, PV array simulators can be quite expensive and some practical problems have been observed during laboratory tests:

- Simulators based on controlled switching mode devices can inject DC ripple on the I-V curve. This ripple can adversely affect MPPT behaviour. Moreover, under such conditions, determination of the exact value of P_{MAX} may be more difficult
- If the PV array simulator consists of a network of many diodes (and resistors), care must be taken that the diodes are at the same temperature during measurement of MPP and during the actual MPPT operation.
- The combination of a PV array simulator and an MPPT may oscillate, or (depending on the design) the MPPT may influence and alter the I-V characteristic of the simulator. Controlled switching mode simulators are especially prone to this problem.

This static test can be repeated at a variety of PV operating conditions to provide curves of $\eta_{MPPT.E}$, $\varepsilon_{MPPT.V}$, and $\varepsilon_{MPPT.I}$.

2.2. Assessment of Dynamic MPPT Performance

The dynamic behaviour of the MPPT algorithm - e.g. on cloudy days with frequent and rapid changes of irradiance - is not reflected in the static figures. In locations where such conditions predominate, this dynamic behaviour is also an important issue.

The purpose of this test is to measure $\varepsilon_{MPPT.V}$, $\varepsilon_{MPPT.I}$, and $\varepsilon_{MPPT.P}$, under dynamic conditions and as functions of important parameters.

Measurements are executed under varied parameters and defined conditions. The dynamic parameters could follow triangle-shaped signal functions (sweeps), where $^{dVmax}/_{dt}$ or $^{dPmax}/_{dt}$ can be varied, together with sweeping through V_{MAX} or P_{MAX} at the same time. Responses to step functions (e.g. stepping from 10% to 100% of nominal power) are however easier to achieve. Also are most MPPT algorithms quite slow (response time of many seconds up to minutes), while irradiance may change within 300 milliseconds or less.

Resulting plots display the MPPT errors as functions of V_{MAX} , P_{MAX} , $^{dVmax}/_{dt}$, and $^{dPmax}/_{dt}$.

Measurement equipment comprises a dynamic programmable PV array I-V curve simulator, a function generator, and meters and instrumentation (possibly interconnected for control and automated).

For dynamic assessment and measurements, a programmable PV array simulator with real-time signal output of $P_{MAX}(t)$, $V_{MAX}(t)$ and $I_{MAX}(t)$ is necessary, so that actual and MPP values can be directly compared [2],[3],[4], (see figure 4).

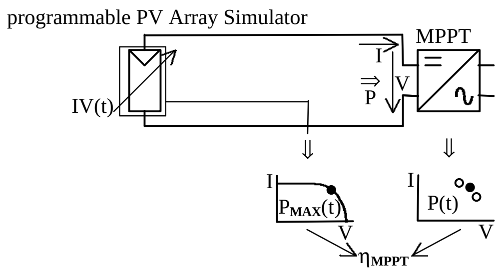


Figure 4: Dynamic laboratory measurements

2.3. Assessment of Energetic Efficiency

The purpose of these tests is to determine the MPPT energetic efficiency $\eta_{MPPT.E}$ under various sets of conditions, covering ambiental factors and system design parameters.

Measurement equipment comprises a dynamic programmable PV array I-V curve simulator, a function generator (profile re-player) to reproduce sequences for simulator control, and meters and instrumentation (possibly interconnected for control and automated).

Measurements are executed under varied parameters and defined conditions (sequences). It is proposed to let the dynamic sequences represent various climatic conditions, PV technologies, and system design parameters (such as voltage and power (mis)match between PV array and MPPT).

Measuring under static conditions indicates energy loss due to continuous MPPT search.

Measuring under dynamic conditions indicates energy loss due to quick changes in irradiance.

Resulting figures quantify, for varied sets of conditions, the effect of MPPT behaviour on the energetic performance of the PV system it is a part of. The argument functions to integration may be displayed over time as well, to verify correctness of the achieved result.

2.4. Further Tests

Additional tests may be considered to complete the assessment of MPPT device behaviour.

2.4.1. Night-Day and Day-Night Transitions

This test provides an assessment of the behaviour around startup and shutdown times.

Resulting figures describe how efficient available daylight is used, and how effectively futile operation at night is avoided.

2.4.2. Ability to Cope With Irregularities

This test provides an assessment of how effectively the MPPT device can cope with possibly occurring irregularities, such as a partially shaded PV array with conducting by-pass diodes and a 'double-kneed' I-V curve, and cloud enhancement phenomena, where irradiance can easily jump up to 1400 W/m^2 (over 1900 W/m^2 have been measured in the mountains).

These tests cover robustness of the employed MPPT algorithm, and of the device itself.

3. FIELD MEASUREMENTS (OUTDOOR)

Outdoor measurements have the advantage that actual MPPT behaviour will be observed with the real PV array thus avoiding potentially unrealistic interactions between the MPPT and PV array simulator. Obtaining the necessary range of parameters outdoors requires co-operative weather as well as access to a variety of PV technologies. The following methods have been identified to determine the MPPT energetic efficiency $\eta_{MPPT.E}$.

3.1. Switching Between MPPT and I-V Tracer

This method has been used by several private companies and institutes [5],[6]. The principle is straight-forward. The operating point of the PV array under normal operation with the MPPT is measured and compared to quasi-simultaneous measurements from an I-V curve tracer (see figure 5).

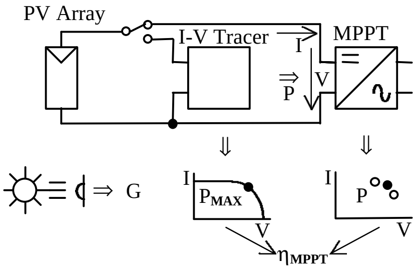


Figure 5: Switching between inverter and IV tracer

In order to give accurate results, it is essential that the ambient conditions do not change significantly between the I-V curve trace and the normal MPPT operation. Variations in irradiance can be corrected by simultaneously measuring the irradiance level and module temperature.

Practical problems encountered with actual measurements include the following:

- If the time needed to measure the I-V characteristic of the PV array is relatively short, fast semiconductor switches are necessary. These switches create some voltage drop that may not be equal for operation with the MPPT and the I-V tracer. If the tracer operates very fast (e.g. 1 ms or even faster), MPPT operation is not affected significantly in most cases. However, fast operation of the I-V curve tracer makes it more sensitive to influences of noise picked up during measurement. Due to inductance of cables to the PV generator, switching the PV current can result in peak voltages and in resonant oscillations with involved capacitors. Also, some cell technologies, especially those with high minority carrier lifetimes, will not give accurate results if I-V curves are swept too quickly.
- If the time needed to measure the I-V characteristic of the PV array is relatively high (e.g. several 10 ms or longer), MPPT operation may have to be halted during the I-V curve tracing, making a restart of the MPPT necessary, which can be a rather annoying and time consuming process. On the other hand, noise problems are much easier to handle in this case, and mechanical switches or manual connections can be used which create less voltage drop.

3.2. Using a Calibrated Reference Module

In this method, I-V curves are taken on a pre-calibrated reference module to determine the actual MPP, while the PV array itself is operating normally with its MPPT (see figure 6).

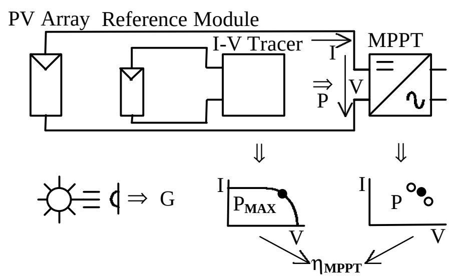


Figure 6: Using a calibrated reference module

In order to estimate the MPP of a PV array from the MPP of one reference module to the MPP, extensive calibration measures have to be performed on the PV array and the reference module.

The reference module must operate under average array conditions (inclination, orientation, mounting method, field of view, wind speed, ambient temperature, etc.). Between tracing I-V curves the reference module must also be operated at a voltage equivalent to the PV array so that it achieves a similar temperature. Differences in soiling between the reference module and the PV array must be minimised as well. In principle it is possible to measure not only static but also dynamic η_{MPPT} with this method.

Possible reasons for errors in determining P_{MAX} with this method are:

- Temperature differences of a few degrees between the reference module and other parts of the PV array are possible.
- Partial shading of the PV array can occur during the measurements.
- Soiling of parts of the PV array may not be equal to that of the reference module.

3.3. Sampling MPPT Input at High Speed

This measurement principle is simple, has low cost and is well suited for field measurements (see figure 7).

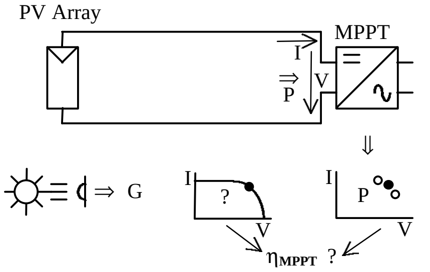


Figure 7: Sampling MPPT input at high speed

The voltage V and current I at the MPPT input are continuously measured at a high sampling speed, typically every 5 ms (to avoid 100 or 120 Hz aliasing errors).

For reference purposes the irradiance should be measured simultaneously with a fast response device (i.e. a silicon-based pyranometer, not a thermopile-based unit), to compensate for variations in irradiance.

In most MPPT designs, the MPPT causes low frequency variations of the DC voltage in the order of 0.1 to 1 Hz. A small 100 or 120 Hz ripple, coming from the AC power pulsation in case of single phase inverters, can be superimposed over this signal [7],[8].

By studying plots of power and voltage over time it can be determined whether the MPP is correctly tracked. Oscillations (be it MPPT search or ripple) show correlated variation of P and V below the MPP (i.e. power rises with voltage), while P and V are anti-correlated above the MPP (i.e. power falls with rising voltage).

P_{MAX} can be obtained from a regression of successive readings where V and I do not change direction (i.e. continue rising or falling) while P does change direction. It is necessary that the sampled values oscillate around the MPP.

3.4. Using Manual Mode to Obtain I-V Curve Data

Some MPPTs provide the capability to manually adjust their operating point, i.e. they allow the operator to pre-set either the voltage or current flowing into the MPPT and therefore determine where on its I-V curve the PV array is actually operating. By manually sweeping the values and noting the actual power, the MPP can effectively be determined.

In a second step, the MPPT is switched to the automatic MPPT mode, and operating values are then compared to the MPP. Irradiance should be recorded to compensate for actual variations during that measurement (see figure 8).

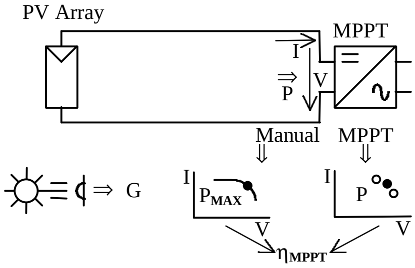


Figure 8: Using manual mode to obtain I-V curve data

This method is by far the simplest to implement and can be done as a quick check of MPPT health. It is, however, much more effective on inverters that provide manually adjustable voltage operation than those that provide manually adjustable current especially under changing irradiance conditions. Additionally, manual operating control capability is not widely available so the use of this method is limited.

3.5. Analysing Monitoring Data

There are several approaches for using data collected from operating PV systems to determine how accurate the MPPT is operating. To a first order approximation, the MPP current I_{MAX} is dependent solely on the in-plane irradiance G. If the MPPT works correctly, the input current I should be close to I_{MAX}. Since the proportionality between G and I_{MAX} is a linear relation, it is valid not only for instantaneous values, but also for integrals such as sums or average data (see figure 9).

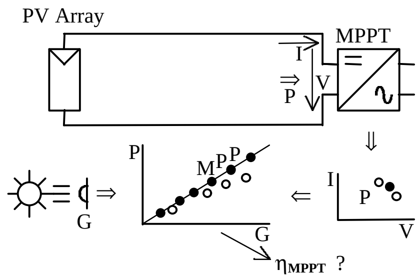


Figure 9: Analysing monitoring data

The proportionality between G and I is a necessary condition for the correct operation of the MPPT, but in order to be completely sure that the I-values coincide with the I_{MPP}-values it is necessary to check that at least one of the points on the plot of I versus G is the I_{MPP}-value for the corresponding irradiance G. This can be done by one measurement of the PV array IV characteristics.

Also, a scatter diagram (based on 10 minutes averaged measuring values) with the temperature corrected PV array efficiency and the PV array voltage versus the irradiance can be displayed. A diagram of irradiance, PV array voltage, and PV array power versus time makes the working of MPPT evident as well. This way, static as well as dynamic

MPPT inaccuracies can easily be identified, and many problems with MPPT have been solved in the past (see poster P5B.11, [9]). Assessing the PV array operating voltage along with PV array efficiency is essential to avoid erroneously concluding MPPT inaccuracy.

Monitoring data can also be used with more sophisticated modelling or I-V curve translation techniques and a well characterised array. For example the methods used by ESTI [10] and by Sandia [11] both can be used to estimate I_{MAX} and V_{MAX} for a given set of ambient conditions, for comparison to the array operating data recorded in the data file.

Operational data from projects monitored according to the Guidelines for the Assessment of Photovoltaic Plants (Document A - Photovoltaic Systems Monitoring) [12] contain the hourly averages of both G and I. Other projects, such as PVUSA and TEAM-UP in the USA, also collect the appropriate weather and system performance data.

Like in method 3.2 (using a calibrated reference module), partial shading and differences of irradiation and soiling within the PV array may influence the results obtained.

4. SUMMARY AND CONCLUSIONS

Draft definitions of terms and calculations are presented for discussion. A number of measurement methods are available and useful for determining the performance of an inverter's MPPT. The given situation, available equipment, user's needs, and other factors will determine which procedure will be most appropriate. The authors encourage other researchers to provide feedback in the form of variations, corrections, additional steps and precautions, or entirely different procedures.

Our intent is to compile this input and develop a set of consensus procedures for inclusion in an upcoming IEC standard.

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