# Lesson 14

# Thermomechanical Measurements for Energy Systems (MENR)

# Measurements for Mechanical Systems and Production (MMER)

A.Y. 2015-16

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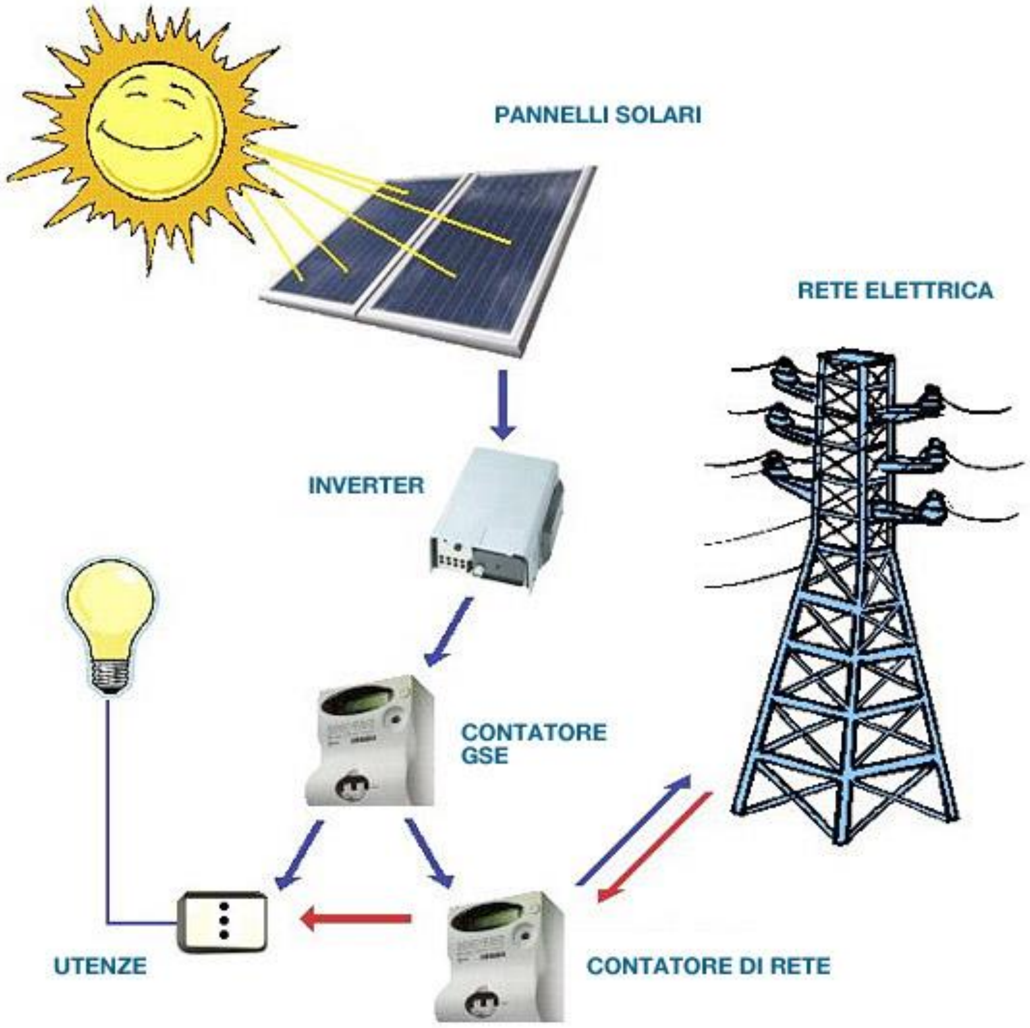
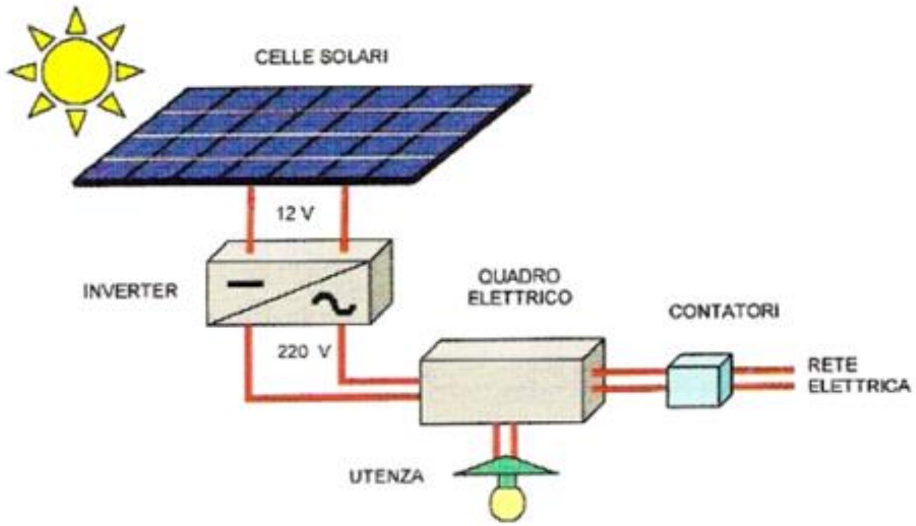
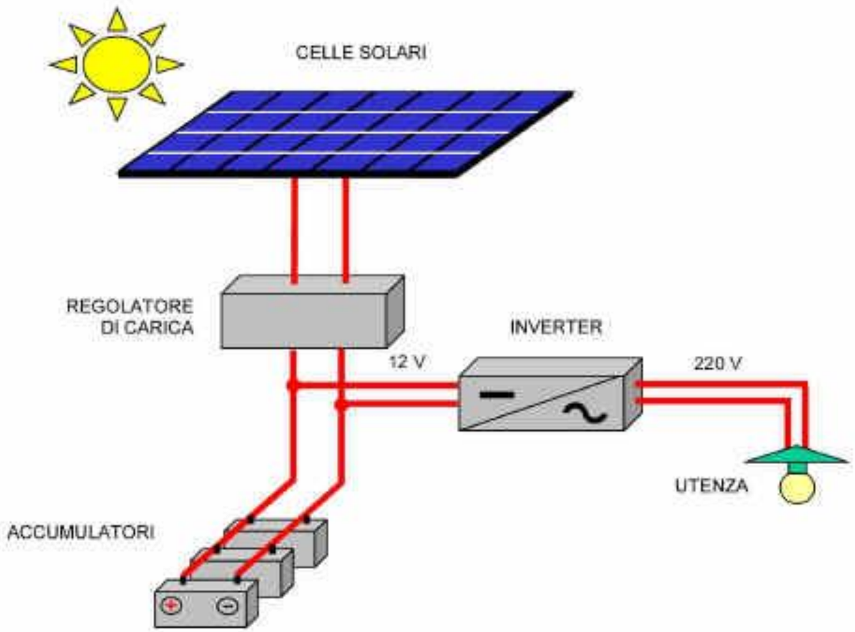
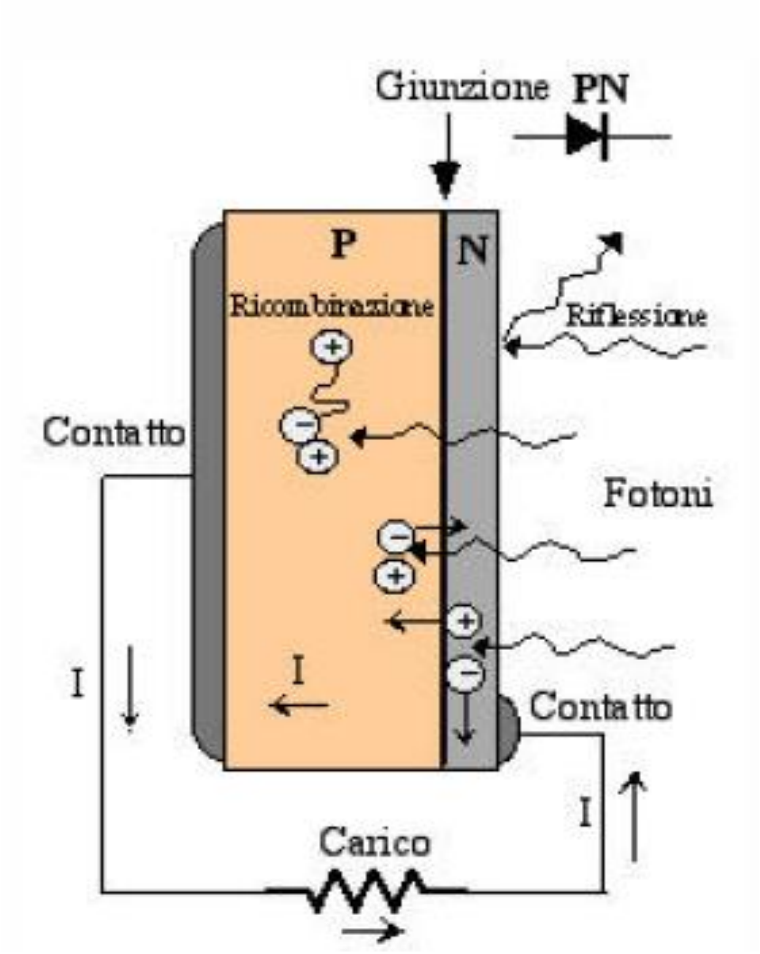
# Solar plant schemes



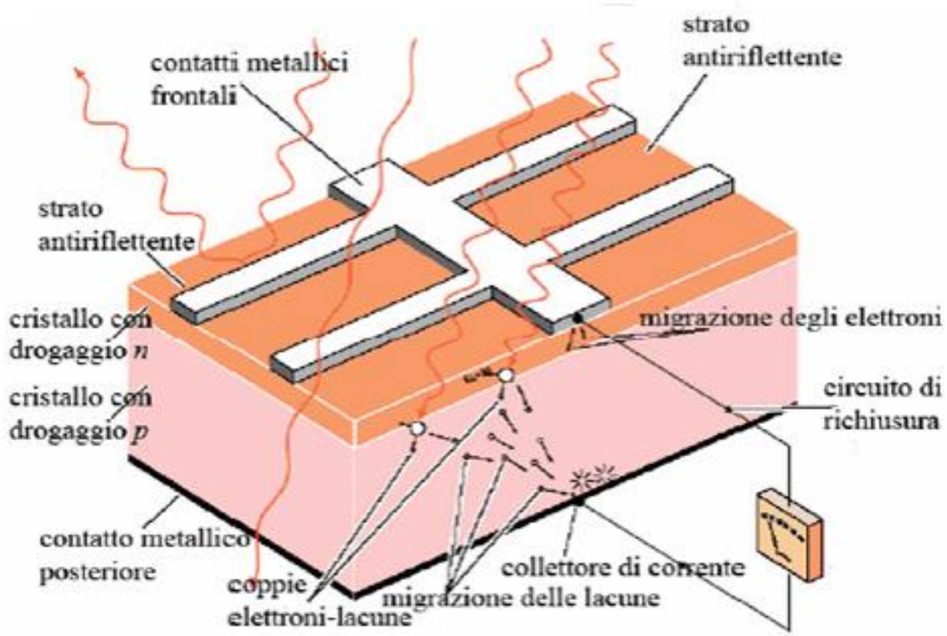
# *Theory elements for the photodiode*




In a very thin layer near the junction (***depletion layer***), the distribution of charge carriers (***electrons and gaps***) changes from the normal situation present in the semiconductor P or N: it creates an electric field (supported by a charge double layer fixed in the lattice). In the depletion layer, there are no free charges and when this layer is struck by light (photons), some electrons, normally linked to an atom of the crystal lattice and thus not available for “charge transport”, are freed from the bondage and become free to move in the Crystal, leaving positively charged the atom to which they were tied. This positive charge is called "gap". Even the gaps can "move" in the Crystal: in fact, if one of the electrons bound to adjacent atoms moves into the vacated site, the “gap moves in the opposite direction”. The two types of charge carriers (*electrons and gaps*) can recombine during migration.

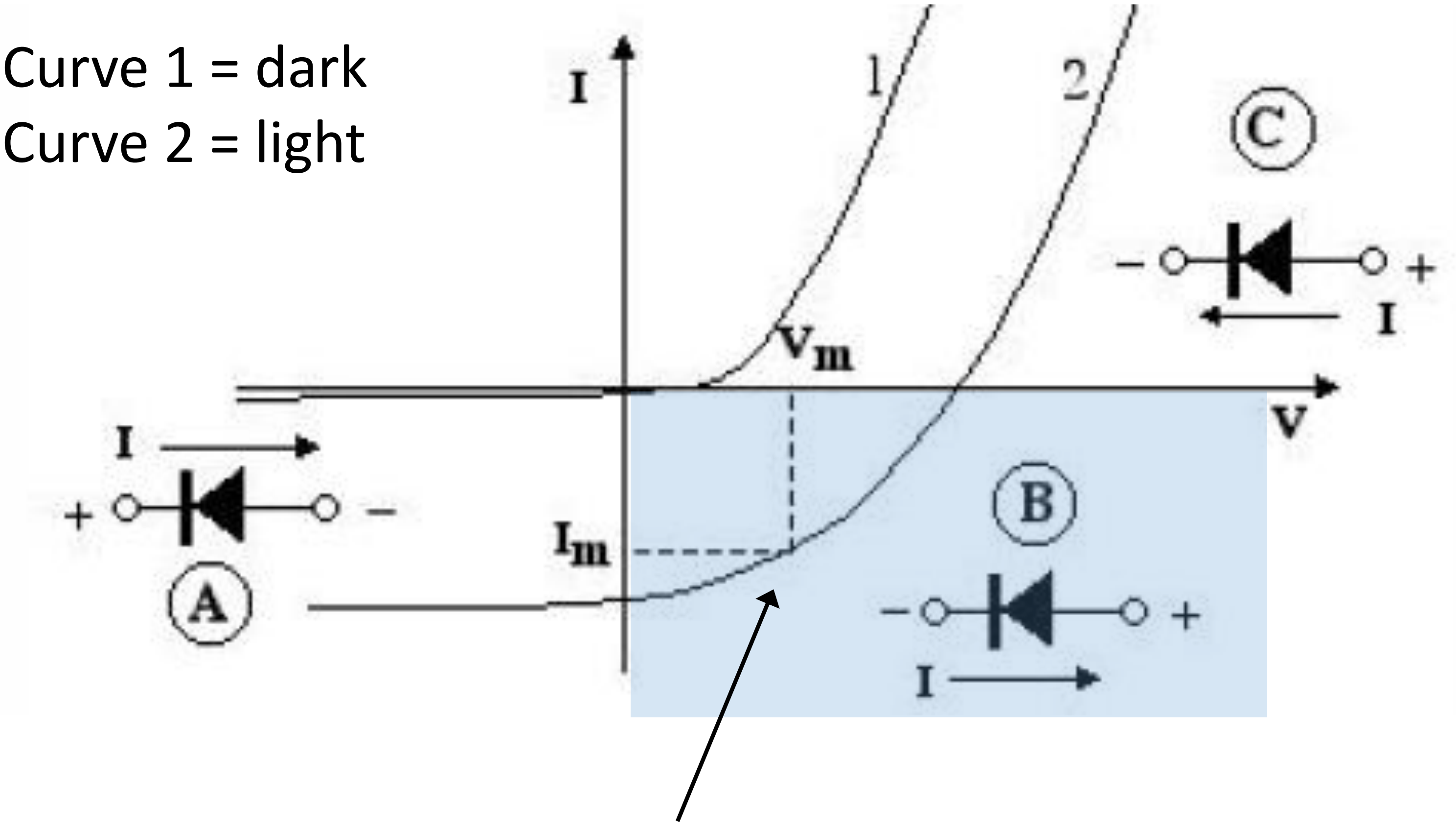
# Elements of photodiode theory

The photo-current can only be produced by a stream of photons (with an energy greater than the *threshold energy* : hν > Eg ) that could reach the "emptying layer". The threshold energy is the one corresponding to the "forbidden energy band" (***Energy Gap***) typical of the semiconductor with which the PN junction is made. A light sensor can then be obtained with a photodiode: it is sufficient exposing to light the PN junction, closed on an external load (for example, by making a very thin layer doped N, as shown in the figure) because through it we establish an electrical current proportional to the light stream, which circulates from P to N on the external load and from N to P inside the photodiode (*reverse current*). Conversely, if a PN junction is crossed by electric current in the direction of the positive bias (*direct current*), it is possible to observe an emission of light (LED).



# Characteristic curves of the photodiode

Curve 1 = dark
Curve 2 = light




**B: photodiode in <u>photovoltaic production</u> (polarized directly, but as we would have $R_{internal} < 0$ … connecting an external load, we observe in it a reverse current $I_m$ ):**

C: photodiode *directly polarized* (P > 0 and N < 0) ... normal diode.

A: photodiode *inversely polarized* (P < 0 and N > 0) ... to be avoided !

# *Testing procedure*

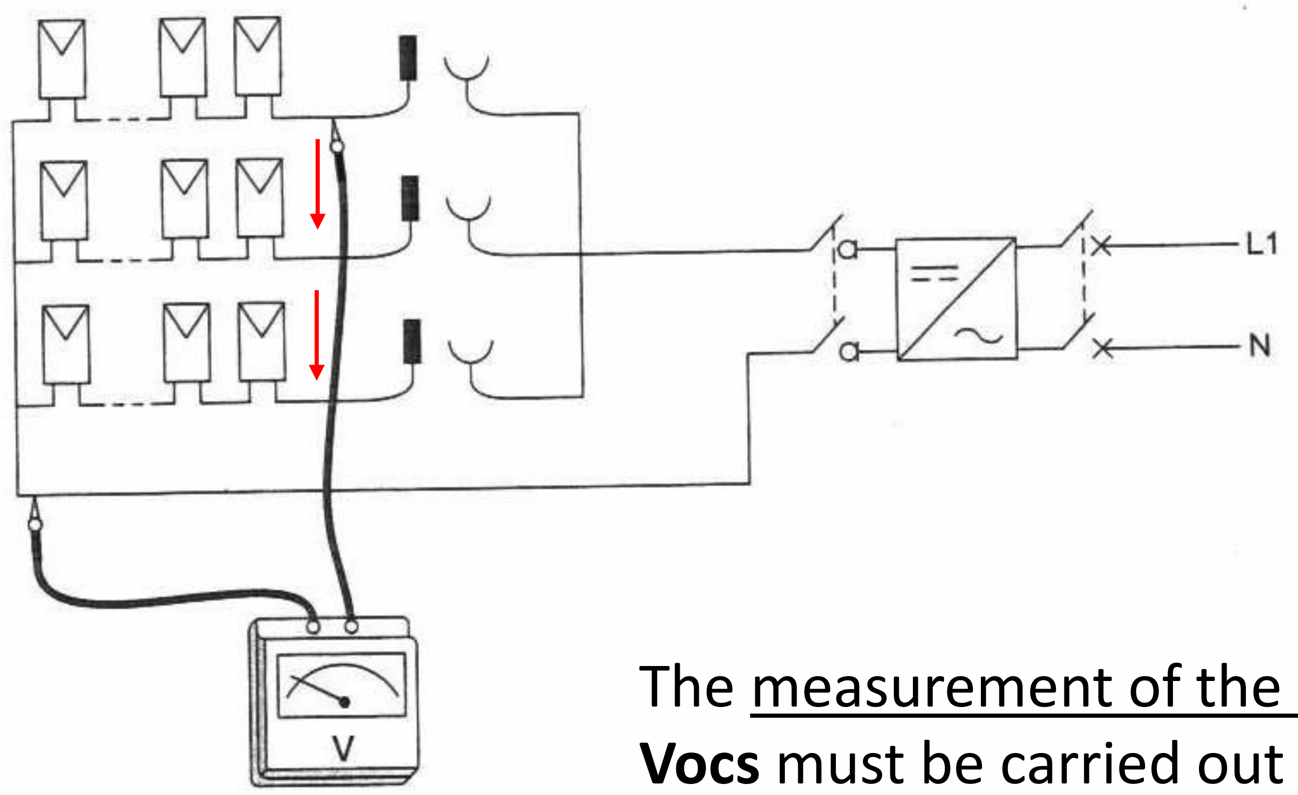
A photovoltaic (PV) system must be subjected to an ***initial test*** (first commissioning) and to ***periodic checks*** (e.g. annually) to be programmed by a “maintenance plan”.

The initial and periodic inspections involve performing:

- **visual examination and checks on:**
  - **the PV mudules**
  - **the cables**
  - **the junction boxes**
  - **the inverter**

- **instrumental tests and measurements:**
  - **of the <u>string current</u> and <u>voltage</u>**
  - **of the insulation**
  - **verification of the PV plant equipotential points**
  - **<u>of the PV plant efficiency</u> with <u>$W_{CC}$ and $W_{CA}$ measurements</u> on each Inverter**

# *Testing procedure*




The <u>measurement of the string voltage</u> **Vocs** must be carried out for each string in constant irradiation conditions; there should not be more than 5% differences between strings (tolerated mismatch)

# *Testing procedure*

To compare the Open Circuit Voltage measured on the string (**$V_{OCS}$**) with the value at STandard Condition (1000 W/m$^2$; 25° C; Am 1.5) specified by the manufacturer on the modules (**$V_{OC-STC}$**), the following equation can be employed

$$\mathbf{V_{OCS} = [V_{OC-STC} - \beta\,(25 - T_{cell})]}\ \boldsymbol{n}$$

$V_{OC-STC}$ = open circuit “standard condition” voltage of the module (V)
β = coefficient of voltage variation with the temperature (V/° C)
$T_{cell}$ = temperature measured at the rear of the modules (° C)
n = number of modules in the string

The $T_{cell}$ temperature can be measured by an RTD sensor (for example a $Pt_{100}$ probe) or with a thermocouple, located <u>on the back</u> of one of the modules.  The required measurement accuracy is ± 1° C

# Testing procedure

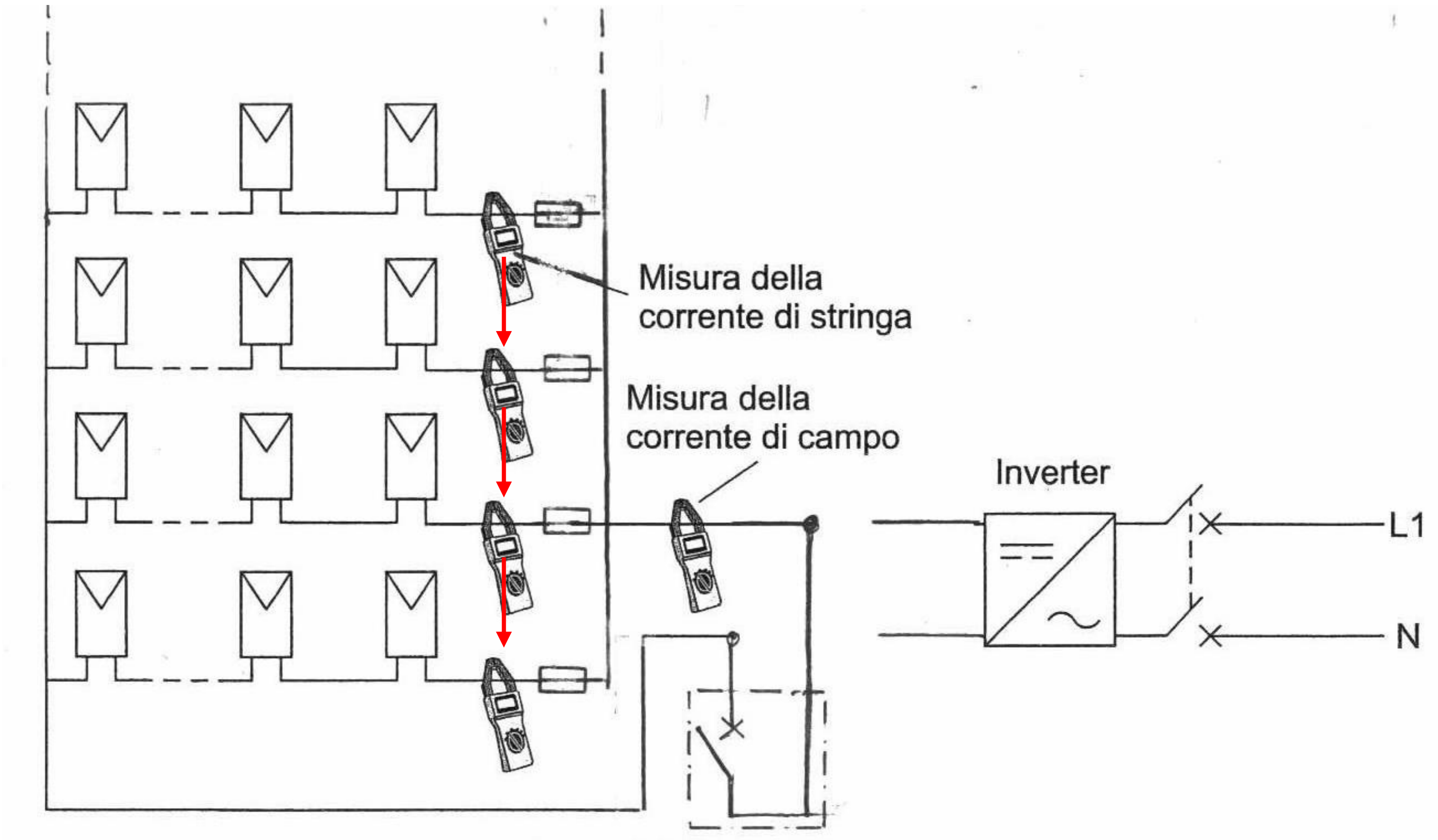
The temperature value $T_{cell}$ can also be obtained by measuring the *environmental temperature* (**$T_{amb}$**) and the *solar radiation* (**$G_p$**) with the approximate relationship:

$$\mathbf{T_{cell} = T_{amb} + G_p\,(NOCT - 20) / 800}$$

NOCT = module Temperature at Nominal Operating Conditions
(G = 800 W/m$^2$; $T_{amb}$ = 20° C; wind speed 1 m/s)

In this way, it is possible to measure the $T_{amb}$ temperature “near the rear” of the modules, without a direct contact with it.
Always avoid the direct radiation of the temperature sensor.

# *Testing procedure*




For safety reasons, the measurements of short circuit current (**$I_{sc}$**) should be done connecting "photovoltaic subfields" in short circuit, with an **$I_{sc}$** current not exceeding 120 ÷ 150 A.
This test is done by using special "electrical cassettes" with appropriate current switches.

# *Testing procedure*

When measuring the whole short circuit current $I_{SC\text{-}camp}$ there is always a reduction of 5% due to mismatch to take into account:

$$\mathbf{I_{SC\text{-}camp} = 0{,}95 \cdot \mathit{n} \cdot I_{SC\text{-}mod}}$$

n = number of parallel strings
$I_{SC\text{-}mod}$ = rated current of one module

At higher temperatures, it is possible to compare the measured current values ($I_{SC\text{-}M}$) with those at STC by the relation :

$$\mathbf{I_{SC\text{-}M} = I_{SC\text{-}STC} + \mathit{n}\,\alpha\,(T_{cell} - 25)}$$

α = coefficient of the temperature variation (° C)
$T_{cell}$ = contact temperature measured at the back of the modules (° C)

# *Testing procedure*

In addition to the examinations and tests that are common to all electrical installations (insulation, electrical continuity of the conductors, operation of circuit breakers, etc.)

In order to ensure the efficiency of the PV plant, it is mandatory to measure at least the powers (**$W_{cc}$**) and (**$W_{ca}$**) ...

**This requirement was also contained in the "inspection certificate" (DM 19/2/07) that had to be drawn up and presented to the GSE for accessing the incentives ...**

# CERTIFICATO DI COLLAUDO

**DM 19 febbraio 2007**

NUMERO IDENTIFICATIVO IMPIANTO: ______________

Impianto fotovoltaico installato presso: ______________________ .

Il/La sottoscritto/a professionista/impresa ______________________ ,

**DICHIARA**

quanto segue:

1) la corrispondenza dell'impianto realizzato alla documentazione finale di progetto;
2) di aver verificato l'esistenza della dichiarazione di conformità dell'impianto alla regola dell'arte ai sensi della legge 46/90 sottoscritta dall'installatore (con abilitazione lettera a);
3) la potenza nominale dell'impianto risulta pari a _____ kW, quale somma delle potenze nominali dei moduli costituenti il campo fotovoltaico;
4) hanno avuto esito positivo tutte le seguenti verifiche:
   - *continuità elettrica e connessioni tra moduli* (continuità elettrica tra i vari punti dei circuiti di stringa e fra l'eventuale parallelo delle stringhe e l'ingresso del gruppo di condizionamento e controllo della potenza);
   - *messa a terra di masse e scaricatori* (continuità elettrica dell'impianto di terra, a partire dal dispersore fino alle masse e masse estranee collegate);
   - *isolamento dei circuiti elettrici dalle masse* (resistenza di isolamento dell'impianto adeguata ai valori prescritti dalla norma CEI 64-8/6);
   - *corretto funzionamento dell'impianto fotovoltaico* nelle diverse condizioni di potenza generata e nelle varie modalità previste dal gruppo di conversione e controllo della potenza (accensione, spegnimento, mancanza rete del distributore, ecc.).
5) hanno avuto esito positivo le seguenti verifiche:
   (da effettuare per ciascun "generatore fotovoltaico", inteso come insieme di moduli fotovoltaici con stessa inclinazione e stesso orientamento):
   a) Pcc > 0,85 x Pnom x I / Istc
      dove:
      - Pcc = potenza in corrente continua misurata all'uscita del *generatore fotovoltaico*, con precisione migliore del ±2%;
      - Pnom = potenza nominale del *generatore fotovoltaico*;
      - I = irraggiamento misurato sul piano dei moduli, con precisione migliore del ±3%;
      - Istc = 1000 W/m² (irraggiamento in condizioni di prova standard);

   b) Pca > 0,9 x Pcc
      dove:
      - Pca = potenza attiva in corrente alternata, misurata all'uscita del gruppo di conversione della corrente continua in corrente alternata, con precisione migliore del ±2%.

Le prove di cui ai punti a) e b) devono essere effettuate per I > 600 W/m².

Qualora nel corso delle verifiche venga rilevata una temperatura sulla faccia posteriore dei moduli fotovoltaici superiore a 40 °C è ammessa la correzione in temperatura della potenza misurata come indicato nell'allegato 1 del DM 19 febbraio 2007.

Dichiara, infine, che:

- tutte le verifiche indicate dal punto 1) al punto 5) sono state effettuate in ottemperanza a quanto previsto dalla normativa vigente e, in particolare, dalla normativa specificata dal DM 19 febbraio 2007 e successive modifiche ed integrazioni;
- tutto quanto sopra riportato è corrispondente a verità.

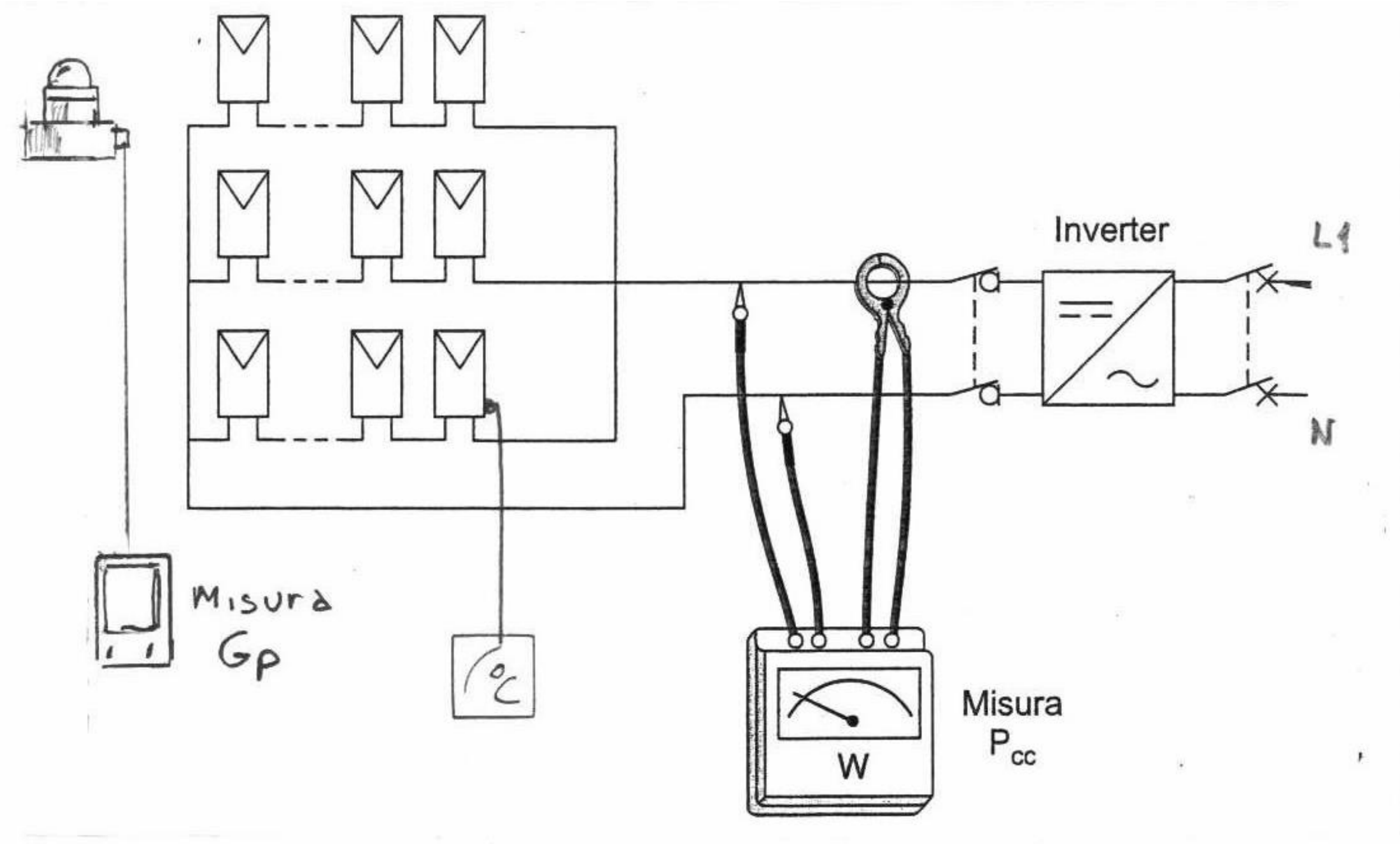
Data di elaborazione del certificato di collaudo: _____ /_____ /_____

Timbro e Firma: ______________________________

# *Acceptance Certificate*

**Checks provided for point 5 of the "Acceptance Certificate"**
**(*PV generator efficiency*)**

- ***Verification of the condition:*** $W_{cc} > 0{,}85 \cdot W_{nom} \cdot G_p/G_{STC}$

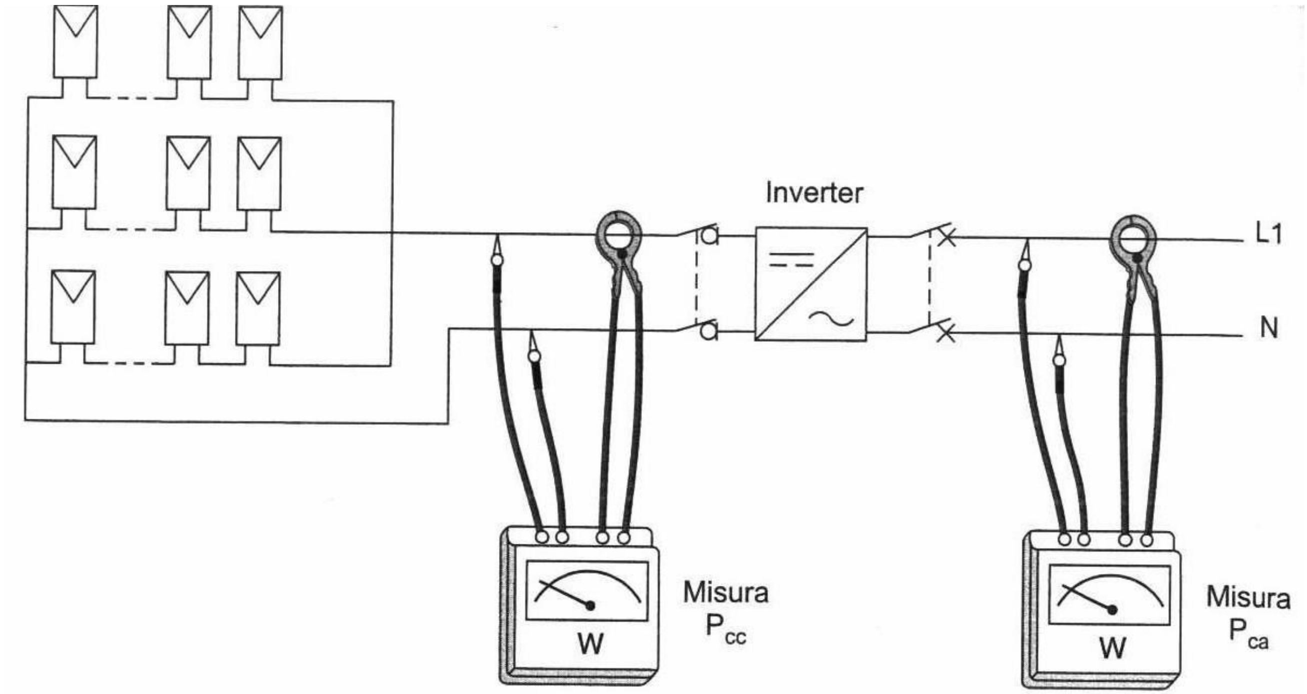


# *Acceptance Certificate*

- The measurement of irradiation **Gp** must be made with a *pyranometer* or a *solarimeter* with an accuracy better than ± 3%
- The power measurement (**Wcc**) at the exit of the PV generator must be carried out with an accuracy better than ± 2%
- The test shall be carried out with solar radiation > 600 $W/m^2$
- The measurements must be carried out on strings or subfields with modules having the same orientation and at the same angle
- It is important that the measurements of **Wcc** and **Gp** are “carried out simultaneously”

# Acceptance Certificate

➢ *Verification of the condition:* **$W_{ca} > 0{,}9\ W_{cc}$**




- DC power measurement (Wcc) at the exit of the PV generator must be carried out with an accuracy better than ± 2%
- AC power measurement (Wca) at the output of the inverter should be carried out with an accuracy better than ± 2%
- The test shall be carried out with a solar radiation > 600 W/m$^2$
- It is important that the measurements of Wcc and Wca are carried out simultaneously

# *Acceptance Certificate*

**If during the measurement of the $W_{ca}$ and $W_{cc}$, the temperature of the modules ($T_{cell}$) exceeds 40° C, we can correct the $W_{cc}$ power measured. The condition to test becomes:**

$$W_{cc} > (1 - P_{tpv} - 0{,}08)\ W_{nom} \times G_p/G_{STC}$$

**$P_{tpv}$ represents the heat loss due to the higher temperature of the modules and is calculated using the following equation:** $P_{tpv} = \gamma\ (T_{cell} - 25)\ /\ 100$

**$T_{cell}$ = measured temperature (with Pt100 probe) on the back of the modules (°C)**

**γ = coefficient of power variation with the temperature (W%/°C)**

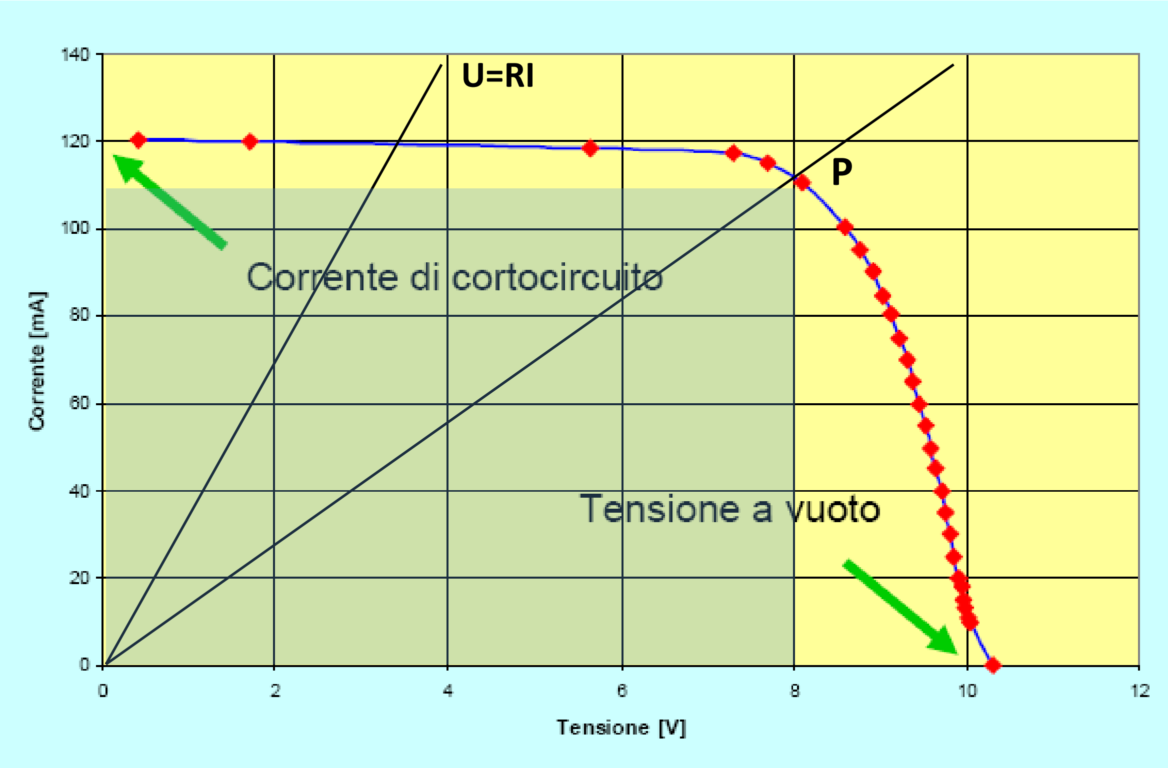
**If we can not measure $T_{cell}$, we can calculate $P_{tpv}$ by measuring the environment temperature (air) in the vicinity of the modules ($T_{amb}$) with the relationship:**

$$P_{tpv} = [T_{amb} - 25 + (NOCT - 20)\ G_p\ /\ 800]\ CT\ /\ 100$$

# What wont we measure ?

**Current-Voltage Characteristic Curve** (es. ATERSA A-240P module data) :
**Voc** = *open circuit voltage* (≈ 37,15V)
**Isc** = *short circuit current* (≈ 8.7 A)

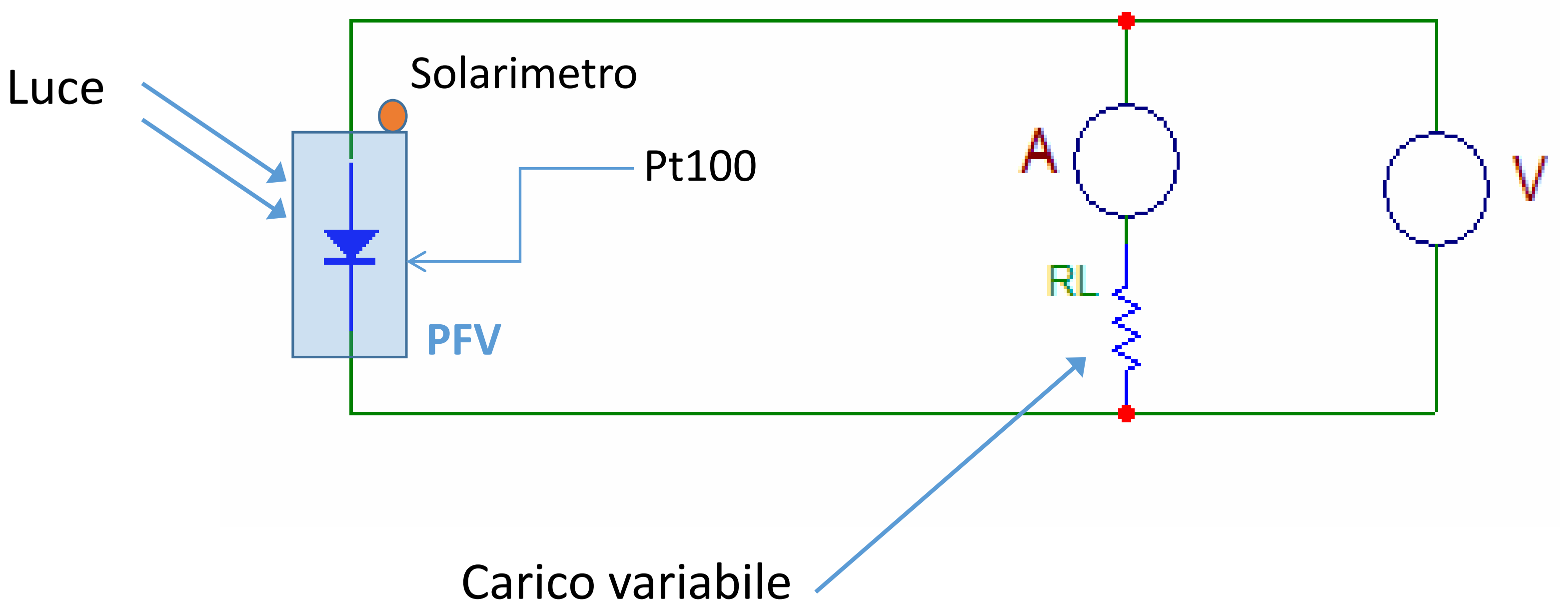
**OPERATING POINT of a PV CELL closed on a LOAD R:**
is the intersection of the current-voltage characteristic curve with the line V = RI. If the operating point corresponds to Imax and Vmax (point P), that condition is the one for which the generator produces its maximum power. In fact, the maximum power delivered by the cell $W_{max} = V_{max} \cdot I_{max}$ is indicated by the highlighted area :



# *Basic test scheme:*

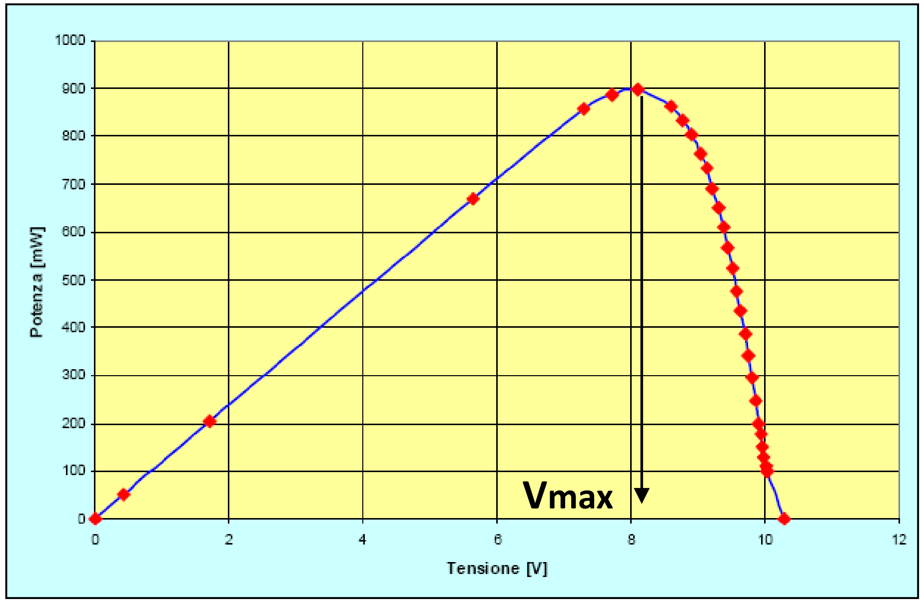
There are available:

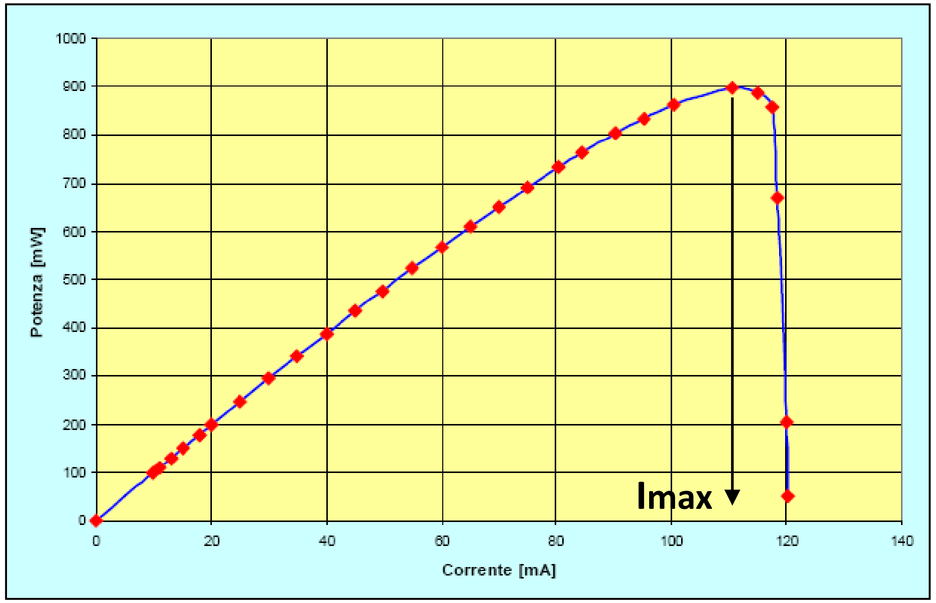
- 1 industrial photovoltaic panel
- A variable resistance load 0.1 Ω – 0.1 kΩ
- an electric thermometer RTD Pt100 or a thermocouple K
- A solar meter for the measurement of solar irradiance



# What wont we measure ?

Starting from the “V” and “I” values measured for each loading condition “R”, we can build the diagrams of the generated power **W = V · I** having the voltage V or the current I as the independent variable :

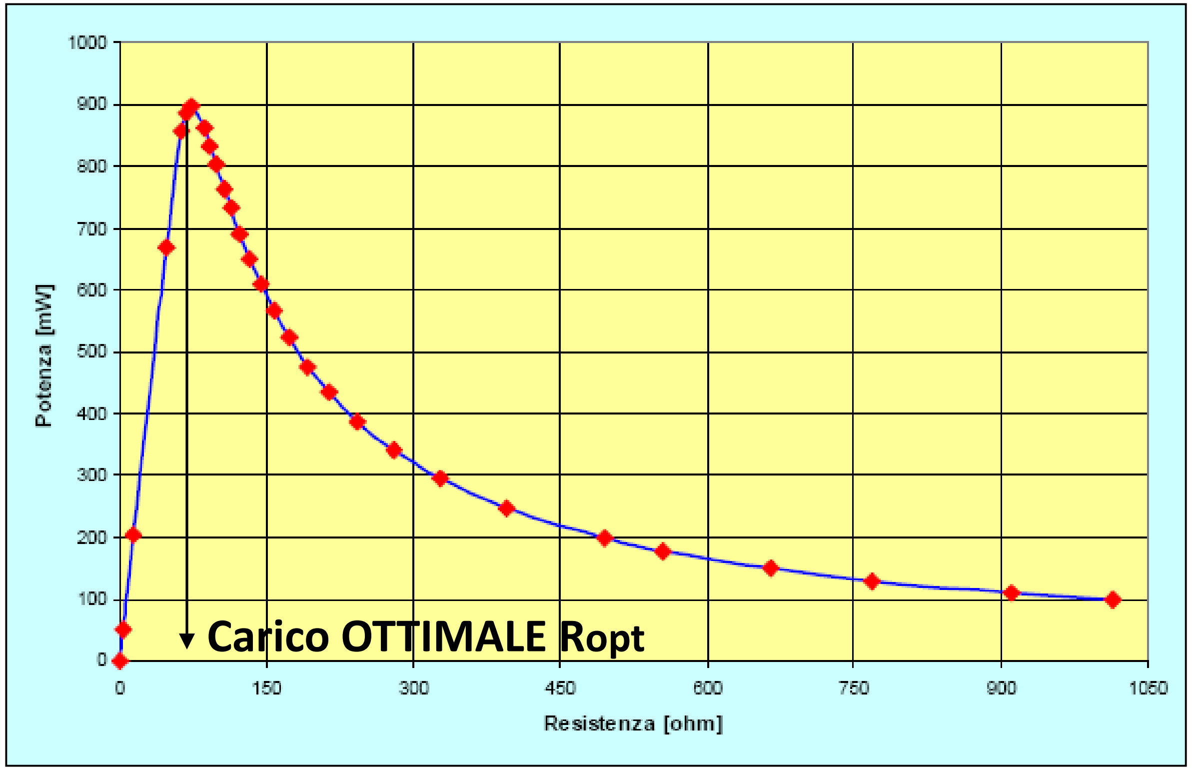



From these diagrams, it is immediate to obtain the values of $V_{max}$ and $I_{max}$ for which the power is maximum !

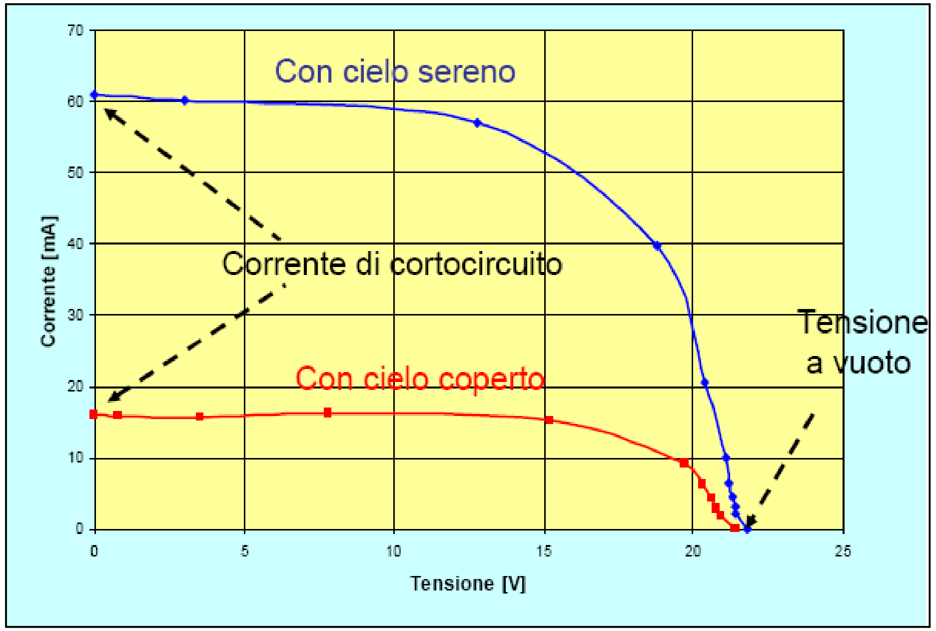
# *What wont we measure ?*

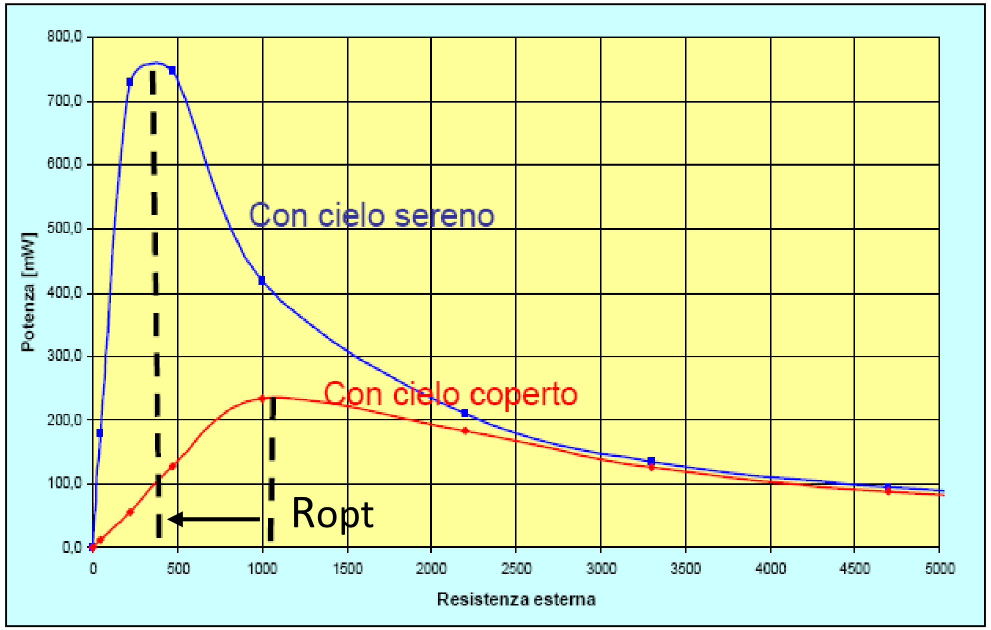
The variable resistance of the load (if we consider negligible the internal resistance of the ammeter) can be extrapolated from the measurements of the current I and the voltage V; for each working point we get : R = V/I.  One can then build the power diagram W as a function of the load R, which yields the value of the *optimal load* ***Ropt*** for which we have the best power transfer Wmax .



# What wont we measure ?

INFLUENCE OF SOLAR RADIATION AND TEMPERATURE:
Unfortunately the I-V characteristic of a PV cell varies as a function of the “solar radiation” and the temperature.
With increasing irradiation, the short circuit current Isc increases.
With increasing irradiation, the optimum load resistance Ropt decreases.
With increasing temperature, the open circuit voltage Voc decreases.




These circumstances should be taken into consideration during the tests and the measurements on the field!

# What wont we measure ?

1. Connect the PV module to the rheostat (variable load) and properly connect to the circuit the instruments for the measurement of V and I
2. Connect the Pt100 thermometer and the solar meter LP RAD 03 BL to their digital multimeters
3. Slowly varying the load on the variable rheostat, simultaneously measure the V and I values for at least 10 working points
4. Build the “diagrams of VI and WR” of the modules. Detect the optimal load resistance for the irradiation conditions encountered during the test.
5. Check the efficiency η for the PV modules, taking into account the corrections in temperature and establish if the module has "passed the test" to access the incentives of the GSE.
6. Run several performance measures as a result of a “partial surface shadowing” of the PV Panel.