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PV MODULE PERFORMANCE AT S.T.C. AND FIELD CONDITIONS

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Outline

- Introduction to PV performance measurements
  - Measurements at STC
  - Field experiments
  - Normalisation
- Factors affecting PV performance in field conditions
- PV Temperature, PV inclination, irradiance
- Temperature distribution
- Partial shading
- Soiling
- Conclusions

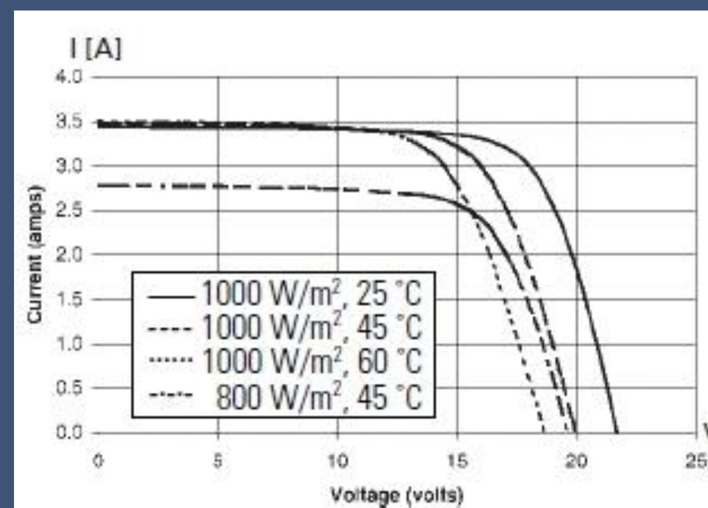
Introduction to PV performance measurements

- PV performance measures
  - Electrical characteristics:

    I_{sc}, V_{oc}, I_m, V_m, P_m, FF, R_s, R_{sh}

    $1/I_{sc}\ (dI_{sc}/dT)$, $1/V_{oc}\ (dV_{oc}/dT)$, $1/P_m\ (dP_m/dT)$
  - I-V curve
- Factory norms
  - Example: SM55 PV module

Solar module SM55		
Electrical parameters		
Maximum power rating P_{max}	$[W_p]$[1)]	55
Rated current I_{MPP}	[A]	3.15
Rated voltage V_{MPP}	[V]	17.4
Short circuit current I_{SC}	[A]	3.45
Open circuit voltage V_{OC}	[V]	21.7
Thermal parameters		
NOCT[2)]	[°C]	45±2
Temp. coefficient: short-circuit current		1.2 mA / °C
Temp. coefficient: open-circuit voltage		-.077 V / °C

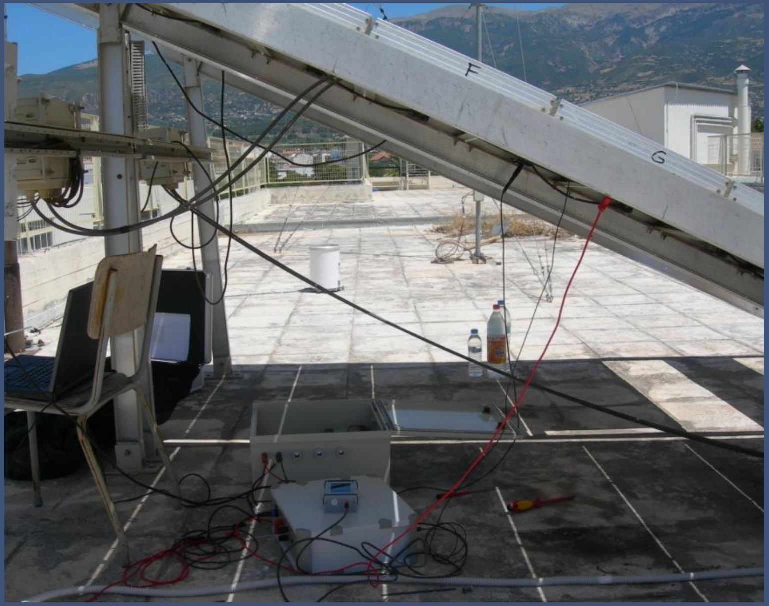


Introduction to PV performance measurements

- Standard Test Conditions (STC)
  - Spectral distribution of Air Mass: 1.5
  - Irradiance: G=1000 W/m^2
  - Panel temperature: Tc= 25°C
- Nominal Operating Cell Temperature (NOCT)
  - Cell temperature under SOC
  - measured in open circuited module
- Standard Operating Conditions (SOC)
  - Ambient temperature: Ta= 20°C
  - Irradiance: G=800 W/m^2
  - Wind speed: v=1 m/sec

Introduction to PV performance measurements

- Experimental measurements
  - Equipment:
    - Portable I-V curve data system
    - Pyranometer/ irradiance sensor
    - Temperature sensor

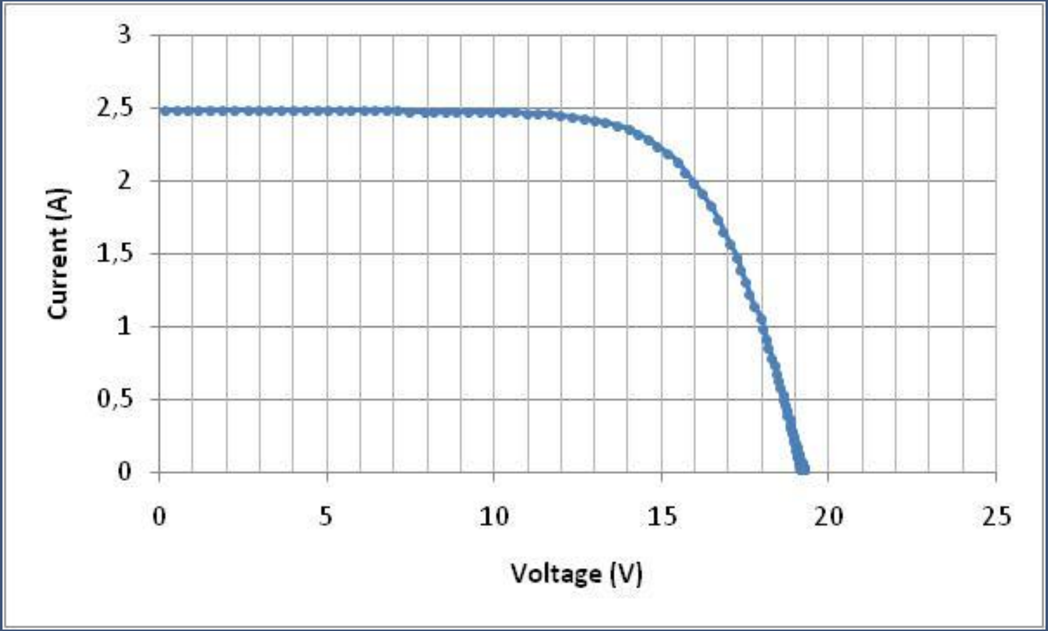


Introduction to PV performance measurements

- Experimental results
  - Example
    - SM55 PV module

G (W/m²)	715,4
Tc (°C)	38,6

	Measured	STC
Isc (A)	2,476	3,445
Voc (V)	19,21	20,18
Pm (W)	33,17	49,03
FF %	69,7	70,5



Normalisation

- Conversion to STC – a simple approach

$$I'_{sc}(STC) = I'_{sc}(meas) / \left(1 + h_{f,Isc} \cdot (T_c - 25^0C)\right) \cdot 10^3 / I_T$$

$$V'_{oc}(STC) = V'_{oc}(meas) / \left(1 + h_{f,Voc} \cdot (T_c - 25^0C)\right)$$

$$P'_m(STC) = P'_m(meas) / \left(1 + h_{f,Pm} \cdot (T_c - 25^0C)\right) \cdot 10^3 / I_T$$

$$FF'(STC) = \frac{P'_m(STC)}{I'_{sc}(STC) \cdot V'_{oc}(STC)}$$

where:
$h_{f,Isc}$: temperature coefficient for I_{sc} in1/K
$h_{f,Isc}$: temperature coefficient for V_{oc} in1/K
$h_{f,Pm}$: temperature coefficient for P_m in1/K

Normalisation

- Conversion to STC based on the following expressions – an elaborated approach

$$I'_{sc}(meas) = I'_{sc}(STC) \cdot \left(1 + h_{f,Isc} \cdot (T_c - 25^0 C)\right) \cdot I_T/10^3$$

$$V'_{oc}(meas) = V'_{oc}(STC) - n_s \cdot 2.3 \cdot 10^{-3} \cdot (T_c - 25^o C) + (m \cdot k \cdot T_c/q) \cdot \ln(I_T/10^3)$$

$$FF^{-1} \cdot \frac{dFF}{dT} = P_m^{-1} \cdot \frac{dP_m}{dT} + i_{sc}^{-1} \cdot \frac{di_{sc}}{dT} + V_{oc}^{-1} \cdot \frac{dV_{oc}}{dT}$$

$$FF'(STC) = FF' + \frac{dFF}{dTc}(25^o C - T_c)$$

$$FF'(STC) = \frac{P'_m(STC)}{I'_{sc}(STC) \cdot V'_{oc}(STC)}$$

where
ns: number of PV-cells in series
k and q are the Boltzman constant and the electron charge

The primed quantities refer to the present state of the PV cell or module.

Conversion to STC

- Direct comparison between actual performance and expected performance based on the factory norms
- Comparison between tests, same point of reference
- Errors introduced in the conversion due to:
  - Equipment accuracy:
    - Irradiance sensor/ pyranometer
    - Temperature sensor
  - Normalisation techniques
    - Unknown temperature coefficients
    - Irradiance translation from horizontal to inclined (if applicable)

Factors affecting PV performance

- External factors
  - Irradiance, Spectrum
  - PV Inclination
  - Climatic conditions
    - Wind
    - Humidity
    - Thermal fluctuations
  - Ambient Temperature
  - Partial shading
  - Soiling, bird pits
  - Cracks
  - Backsheet damage

Factors affecting PV performance

- Internal factors
  - Temperature of module
  - Non-uniform temperature distribution
  - Hotspots
  - Current/ Voltage mismatch between cells and modules
  - Cell impurities, micro-defects, small differences in size
  - Degraded cells/module
- Design methodology:
  - Cell and module technology
  - Connection of modules, bypass diodes
  - Mounting technologies (sun-tracking modes, fixed)

Temperature of PV module in field conditions

- The temperature of the PV module is due to:
  - The solar radiation absorbed by the module which is not converted into current, is dissipated into heat
  - Joule effect I^2R_s
  - Ambient temperature
  - Wind velocity and wind speed
  - PV inclination/geometry

Temperature of PV module in field conditions

- Energy Balance Equation

$$(\tau\alpha)\cdot I_T = \eta_{PV}\cdot I_T + h_{PV,f}\cdot\left(T_{c,f}-T_a\right) + h_{PV,b}\cdot\left(T_{c,b}-T_a\right)$$

(τα): transmission-absorption coefficient
$T_{c,f}$, $T_{c,b}$: PV module temperatures in front and back surface
$h_{pv,f}$, $h_{pv,b}$: surface heat transfer coefficients (W/m^2K) for the front and back surface of the PV module, from Heat Transfer analysis.

- General expression for the Temperature of PV module:

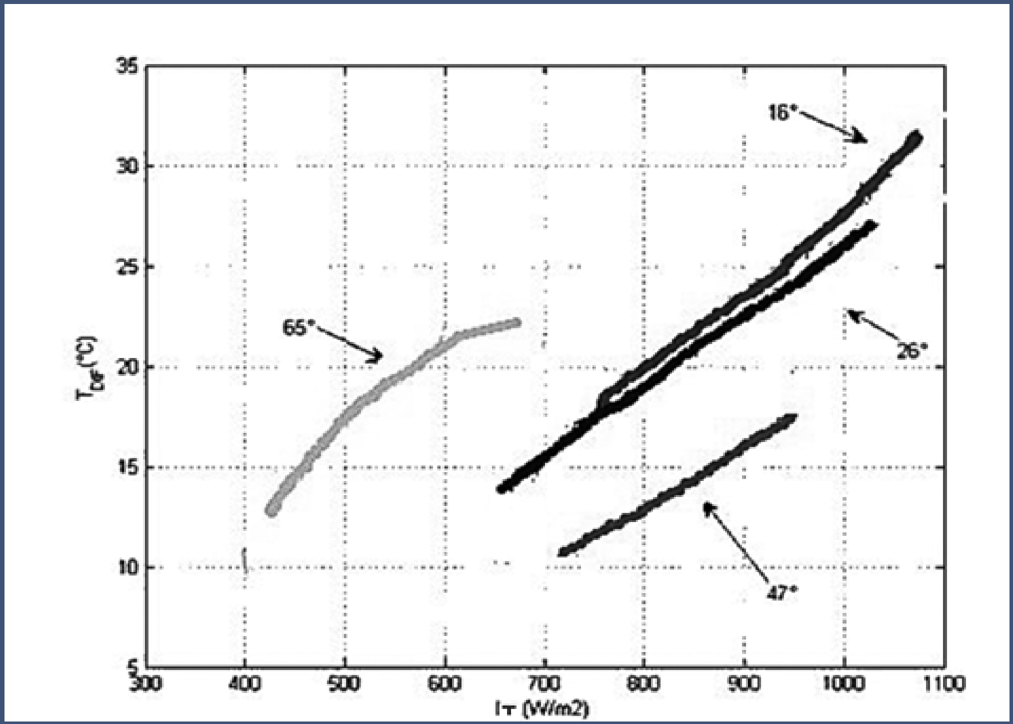
$$T_{PV} = T_a + \lambda\cdot I_T$$

λ: approximately $0.03 m^2\cdot{}^\circ C/W$

- λ is a function of :
  - Inclination angle (h_{pv} depends on this angle)
  - Wind speed, wind direction
  - Type of air flow
  - PV efficiency

Temperature of PV module in field conditions

- Experimental results on (T_{pv}-T_a) vs I_T for various inclination angles



Temperature coefficients of PV module

- Electrical characteristics dependence on PV module temperature

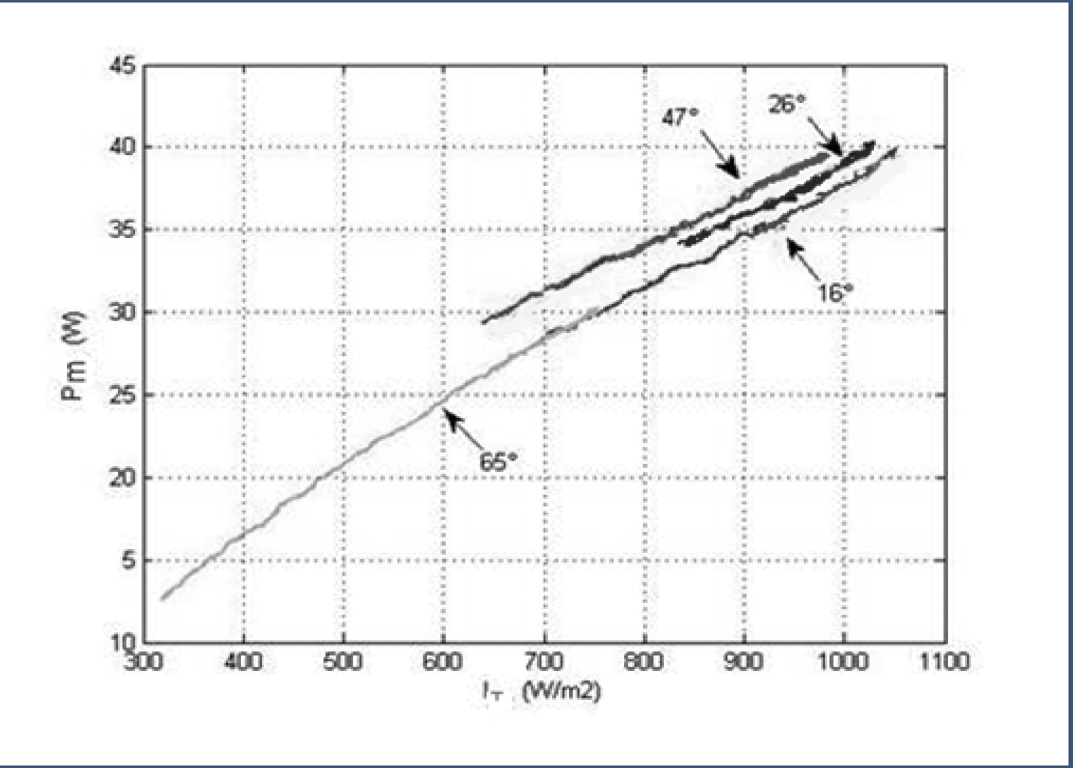
  Indicative values for Si:

  - $1/V_{oc}\ (dV_{oc}/dT) \approx -0.35\% / {}^0C$
  - $1/I_{sc}\ (dI_{sc}/dT) \approx +0.05\% / {}^0C$
  - $1/P_m\ (dP_m/dT) \approx -0.4\% / {}^0C$
  - $1/\eta_{pv}\ (d\eta_{pv}/dT) \approx -0.4\%/{}^0C$
  - $1/FF\ (dFF/dT) \approx -0.7\%/{}^0C$

$$FF^{-1} \cdot \frac{dFF}{dT} = P_m^{-1} \cdot \frac{dP_m}{dT} + i_{sc}^{-1} \cdot \frac{di_{sc}}{dT} + V_{oc}^{-1} \cdot \frac{dV_{oc}}{dT}$$

Temperature of PV module affecting its power output

- Experimental results on P_m vs I_T for various inclination angles

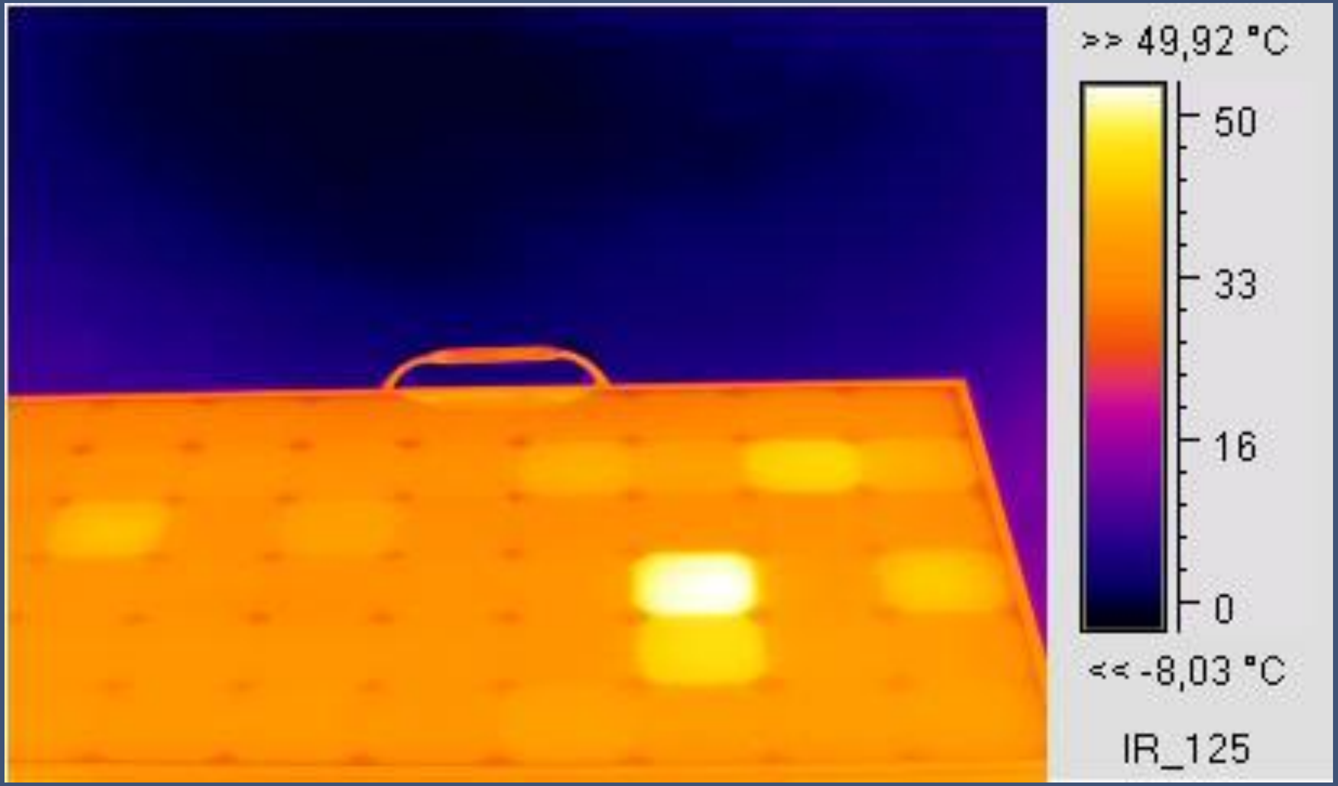


Temperature distribution of PV module during operation in field conditions

- Non-uniform temperature distribution
- IR thermography

IR thermography of a new $50W_p$ sc-Si PV module. Two hot cells exhibit temperature higher by about 6°C from the average temperature of the module.

Temperature distribution of PV module during operation in field conditions

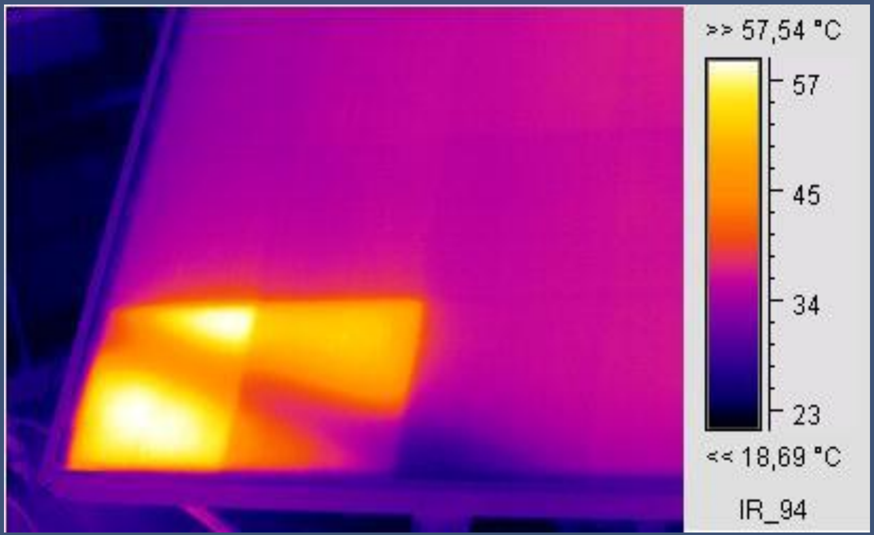


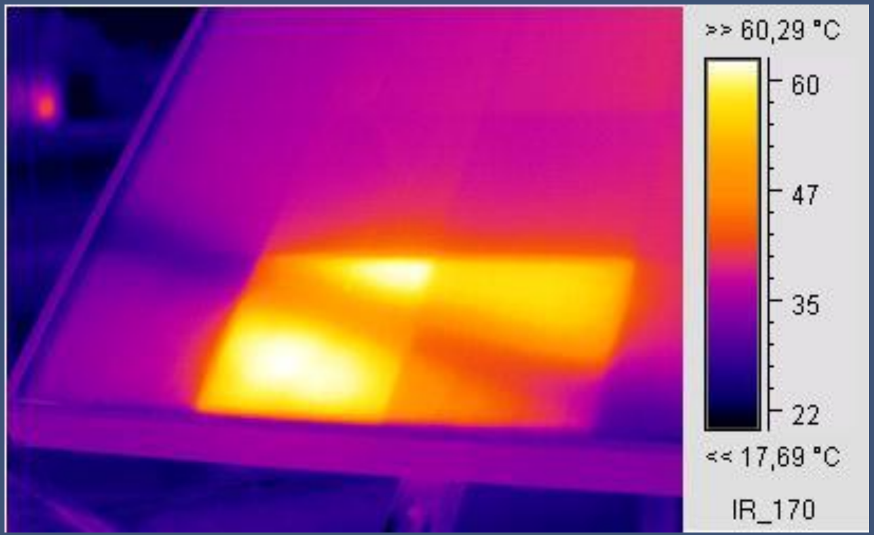
IR thermography of part of a new 175 W_p c-Si PV module during operation. Temperature of hot cell is higher by about 15°C compared to that of its neighbouring cells.

Temperature distribution of PV module during operation in field conditions

- Large temperature difference between cells
  => leads to current/ voltage mismatch
  => power dissipated in the form of heat within the affected cell
  => decrease in the power output
- Temperature difference > 15°C leads to substantial reduction in the power output and may lead to cell and module degradation.

Partial shading effects



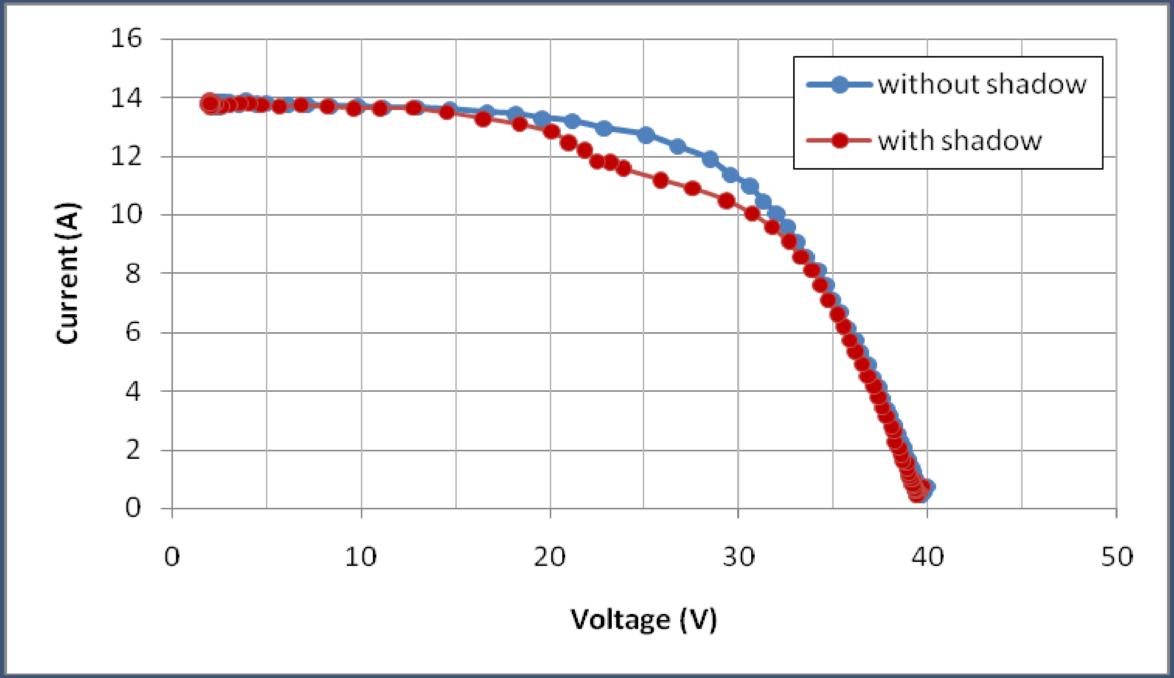


Infrared images of a 2.5 year old PV panel when partially shadowed by a nearby fence. The cells which are temporarily partially covered by a shadow exhibit a temperature increase >25°C compared to the temperature of their neighbouring cells.

Partial shading effects

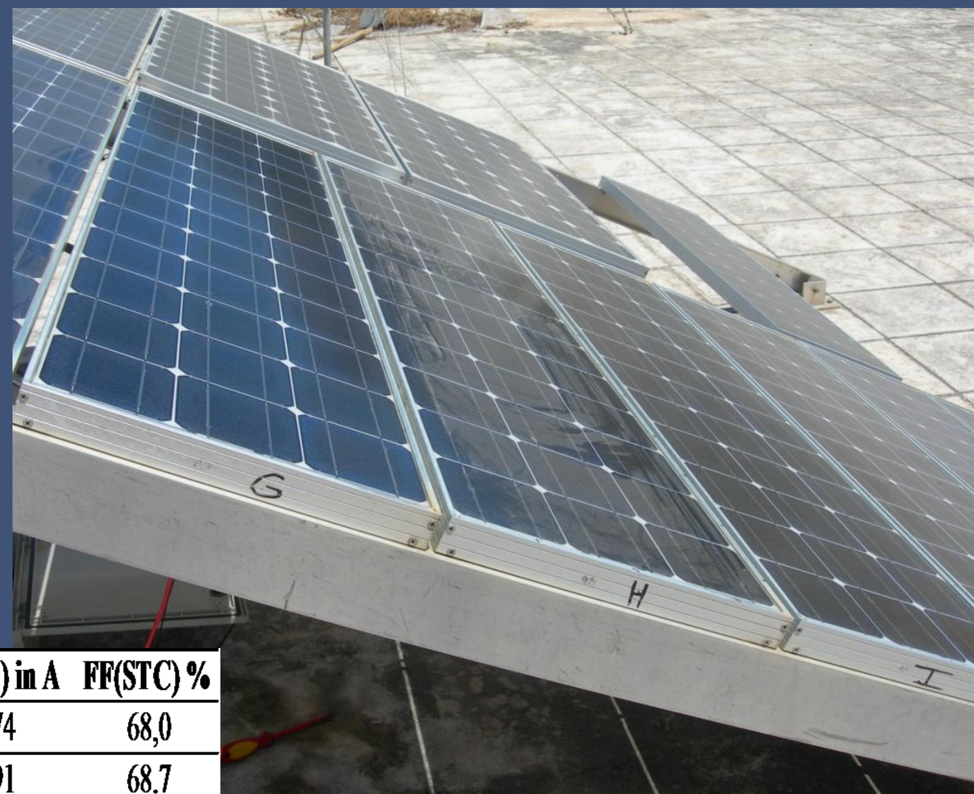
Effect of partial shading on the I-V curve

- Current drop at MPP point leading to substantial reduction in the power output



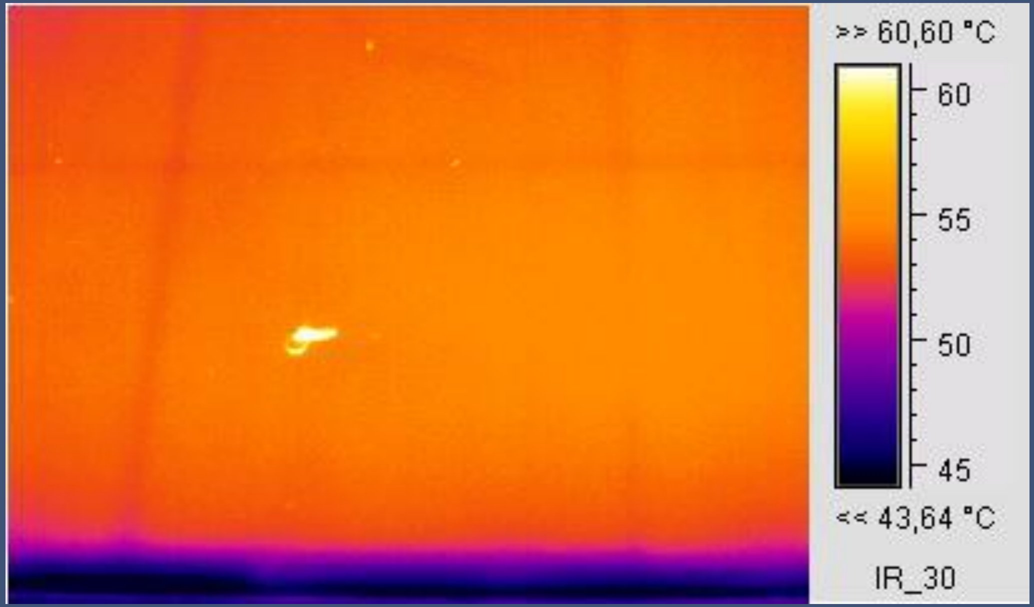
Soiling Effects

- Experimental Results on the effect of naturally developed dust on the electrical characteristics of the PV module



	Pm (STC) in W	Voc(STC) in V	Isc(STC) in A	FF(STC) %
dusty panel	50.37	19.83	3.74	68,0
clean panel	53.01	19.74	3.91	68.7

Effects of Dirt - Bird pits



Digital and IR image of a cell partially covered by a bird pit.
This creates partial shading effect.

Conclusions (1)

- The temperature distribution of PV modules is not uniform.

- The IR thermography is an important tool providing information about the temperature distribution in modules and assisting in the identification of provisionally problematic cells. These cells exhibit higher temperatures causing current and voltage mismatch, which may later develop into hot spots.

- The I-V curve if studied in-depth can reveal even small defects. It may assist in the identification of cells causing a current drop and reveal potential defects, giving an estimate of the degree to which they affect module performance.

Conclusions (2)

- Cells in a module are not ageing in the same pace.
- Highly uneven temperature distribution in new modules may identify potentially higher risk of cell and module degradation.
- High temperatures even at early PV module life may lead, with the contribution of other factors, to hot spots or hot cells, and further to ageing effects such as EVA browning, delamination, leading to progressive power degradation.
- Early diagnosis and regular monitoring of PV modules from as early as initial operation is very important for the identification of potential problematic cells and potential risks.

Related Work in the RES Lab, TEI of Patras

- E. Kaplani (2012). Detection of degradation effects in field-aged c-Si solar cells through IR thermography and digital image processing. *International Journal of Photoenergy*, Vol. 2012, Article ID 396792, pp.1-11.
- S. Kaplanis, E. Kaplani (2011). Energy performance and degradation over 20 years performance of BP c-Si PV modules. *Simulation Modelling Practice and Theory*, Vol. 19, pp. 1201-11.
- E. Kaplani (2012). Design and performance considerations in stand-alone PV powered telecommunication systems. Journal of Engineering Science and Technology Review, Vol. 5(1), pp.1-6.
- E. Kaplani, S. Kaplanis (2012). Temperature distribution effects in PV modules operating in field conditions. Proc. 5th Int. Conf. on Sustainable Energy & Environmental Protection (SEEP 2012), 5-8 June, Dublin, pp.256-261.