UNIVERSITÀ DELLA CALABRIA

UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI **INGEGNERIA MECCANICA, ENERGETICA E GESTIONALE**

unite! University Network for Innovation, Technology and Engineering

WORKSHOP –UNITE!
CSP-IMT

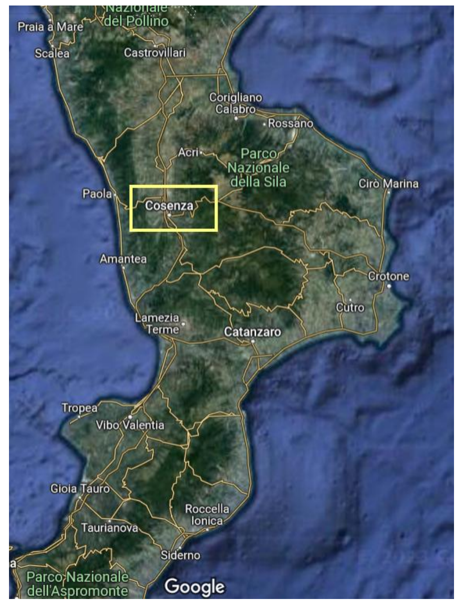
University of CALABRIA

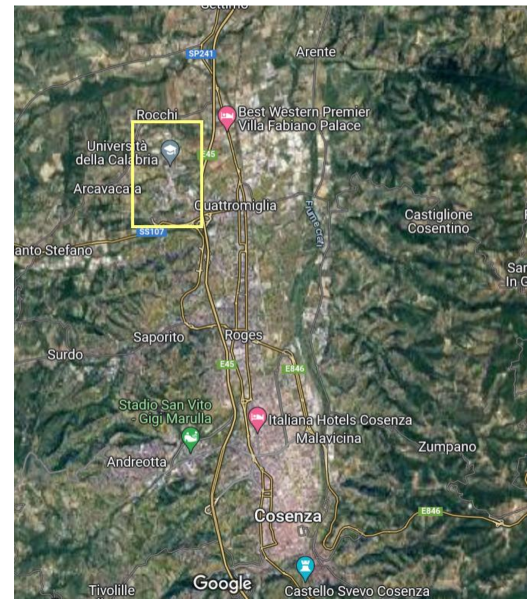
Department of Mechanical, Energy and Management Engineering

Piero Bevilacqua, Ph.D
Researcher in Tenure Track
University of Calabria

UNIVERSITÀ DELLA CALABRIA

University of Calabria - location





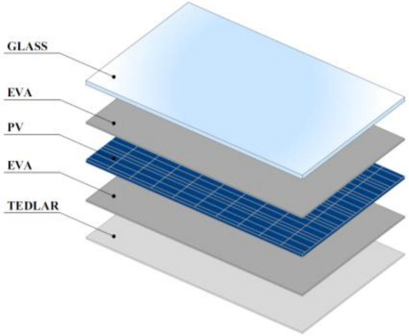
University of Calabria

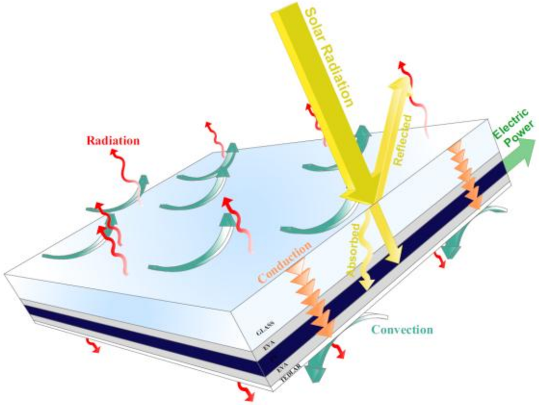
UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI INGEGNERIA MECCANICA, ENERGETICA E GESTIONALE

PHOTOVOLTAIC

Cooling systems and modeling

THERMAL MODELING OF PV PANELS





The model account for the heat transfer phenomena, discretizing the panel in several nodes. Then the energy balance method is applied to each node.

$$\dot{Q}_{gl} = \frac{\alpha_{gl} \cdot G_{PV} \cdot A_{PV}}{V_{gl}} \qquad T_{sky} = \left(\frac{\phi}{\sigma}\right)^{0.25}$$

$$\dot{Q}_{PV} = \frac{R \cdot A_{PV,cell} \cdot (1 - \eta_{PV})}{V_{PV,cell}}$$

$$h_{rad,surf-sink} = \frac{\sigma \cdot (T_{surf}^2 + T_{sink}^2)(T_{surf} + T_{sink})}{\frac{1-\varepsilon_{surf}}{\varepsilon_{surf}} + \frac{1}{F_{surf-sink}}}$$

$$h_{conv,for} = 3.83 \cdot v_w^{0.5} \cdot l_{ch}{}^{-0.5} \text{ for laminar flow}$$

$$h_{conv,for} = 5.74 \cdot v_w^{0.8} \cdot l_{ch}{}^{-0.2} \text{ for turbulent flow}$$

$$h_{conv,for} = 5.74 \cdot v_w^{0.8} \cdot l_{ch}{}^{-0.2} - 16.46 \cdot l_{ch}{}^{-1} \text{ for mixed flow}$$

Heat conduction in the layer

$$\rho \cdot c \, \frac{\partial T(x,y,z,t)}{\partial t} = k \cdot \left(\frac{\partial^2 T(x,y,z,t)}{\partial x^2} + \frac{\partial^2 T(x,y,z,t)}{\partial y} + \frac{\partial^2 T(x,y,z,t)}{\partial z^2}\right) + \dot{Q}(t)$$

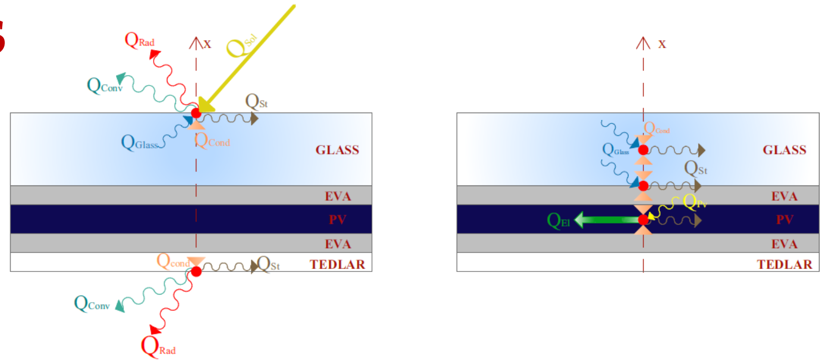
Backward difference

$$\frac{\partial}{\partial t} T(x,t) \approx \frac{T(x,t) - T(x,t-\Delta t)}{\Delta t} = \frac{T_m^p - T_m^{p-1}}{\Delta t}$$

The Finite Difference (FD) method

$$\frac{\partial^2}{\partial x^2} T(x,t) \approx \frac{T(x+1,t) - 2T(x,t) + T(x-1,t)}{\Delta x^2} = \frac{T_{m+1} - 2\,T_m + T_{m-1}}{\Delta x^2}$$

THERMAL MODELING OF PV PANELS



Energy Balance Method

$$\dot{E}_{in} + \dot{E}_g = \dot{E}_{st} + \dot{E}_{out}$$

Top surface node

$$\dot{\mathbf{E}}_{\mathbf{in}} = k_{gl}\left(\frac{T_{m-1}^{p+1} - T_m^{p+1}}{\Delta x}\right) + h_{conv}\left(T_{amb} - T_m^{p+1}\right) + h_{rad,gl-sky}\left(T_{sky} - T_m^{p+1}\right) + h_{rad,gl-ground}\left(T_{ground} - T_m^{p+1}\right)$$

$$\dot{\mathbf{E}}_{\mathbf{g}} = \dot{Q}_{gl}\frac{\Delta x}{2}$$

$$\dot{\mathbf{E}}_{\mathbf{st}} = \left(\varrho_{gl}\cdot c_{gl}\cdot\frac{\Delta x}{2}\right)\left(\frac{T_m^{p+1} - T_m^p}{\Delta t}\right)$$

Interior PV node

$$\dot{\mathbf{E}}_{\mathbf{in}} = k_{PV}\left(\frac{T_{m+1}^{p+1} - T_m^{p+1}}{\Delta x}\right) + k_{PV}\left(\frac{T_{m-1}^{p+1} - T_m^{p+1}}{\Delta x}\right)$$

$$\dot{\mathbf{E}}_{\mathbf{g}} = \dot{Q}_{PV}\cdot\Delta x$$

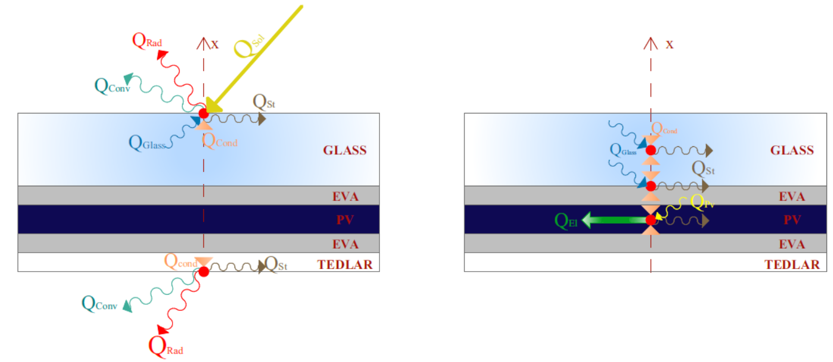
$$\dot{\mathbf{E}}_{\mathbf{st}} = \left(\varrho_{PV}\cdot c_{PV}\cdot\Delta x\right)\left(\frac{T_m^{p+1} - T_m^p}{\Delta t}\right)$$

Applying the energy balance and rearranging the terms it is possible to obtain

$$T_m^{p+1}\left(\frac{\varrho_{gl}\cdot c_{gl}\Delta x}{2\Delta t} + \frac{k_{gl}}{\Delta x} + h_{conv} + h_{rad,front-sky} + h_{rad,front-ground}\right) - T_{m-1}^{p+1}\left(\frac{k_{gl}}{\Delta x}\right) = \left(T_{amb}h_{conv} + T_{sky}h_{rad,gl-sky} + T_{ground}h_{rad,front-ground} + \dot{Q}_{gl}\cdot\frac{\Delta x}{2}\right) + \left(\frac{\varrho_{gl}\cdot c_{gl}\cdot\Delta x}{2\Delta t}\right)\cdot T_m^p$$

$$-\left(\frac{k_{PV}}{\Delta x}\right)T_{m-1}^{p+1} + \left(2\frac{k_{PV}}{\Delta x} + \frac{\varrho_{PV}\cdot c_{PV}\cdot\Delta x}{\Delta t}\right)T_m^{p+1} - \left(\frac{k_{PV}}{\Delta x}\right)T_{m+1}^{p+1} = \left(\dot{Q}_{PV}\Delta x\right) + \left(\frac{\varrho_{PV}\cdot c_{PV}\cdot\Delta x}{\Delta t}\right)\cdot T_m^p$$

THERMAL MODELING OF PV PANELS



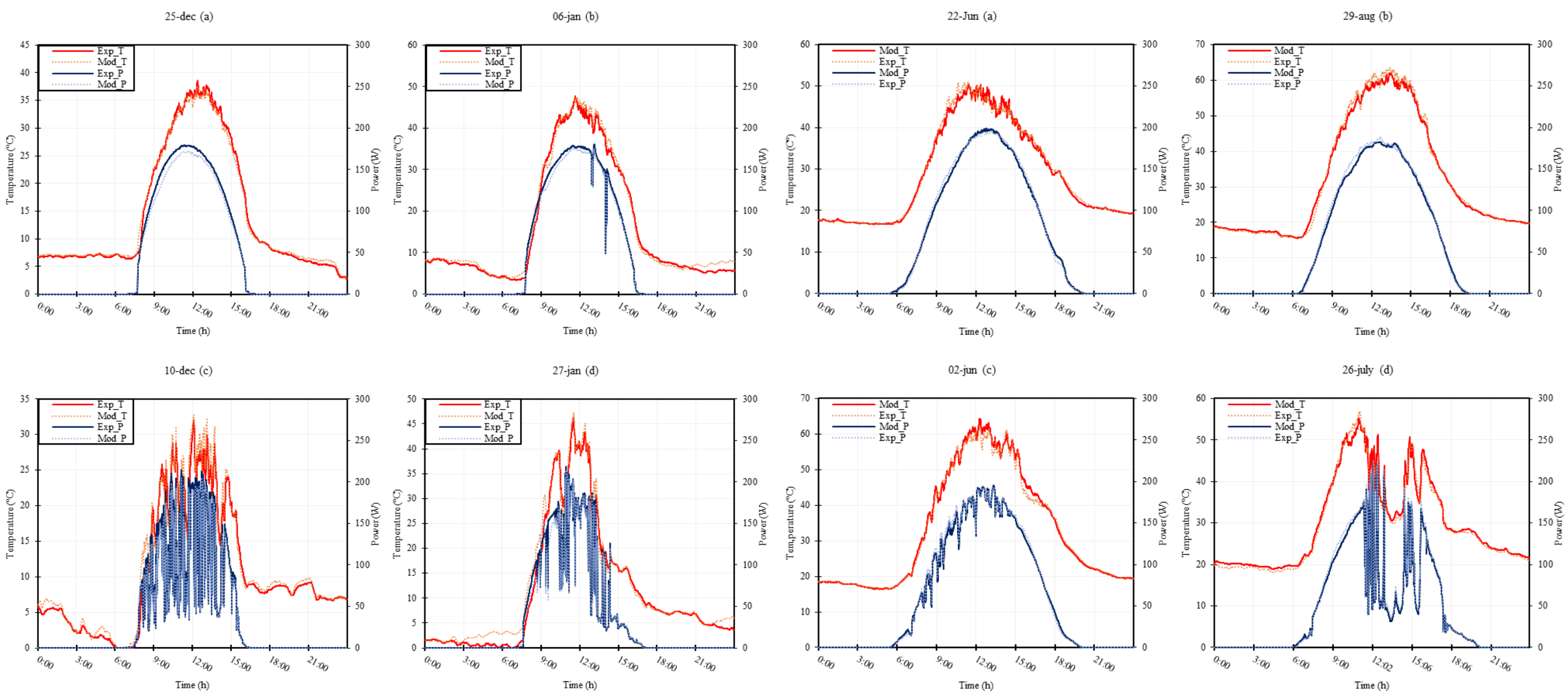
A system of linear equations is obtained by applying the balance equation method to each node

$$\begin{bmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,n-1} & A_{1,n} \\ A_{2,1} & A_{2,2} & & A_{2,n-1} & A_{2,n} \\ \vdots & & \ddots & \vdots & \\ A_{n-1,1} & A_{n-1,2} & \cdots & A_{n-1,n-1} & A_{n-1,n} \\ A_{n,1} & A_{n,2} & & A_{n,n-1} & A_{nn} \end{bmatrix} \begin{Bmatrix} T_1^{p+1} \\ T_2^{p+1} \\ \vdots \\ T_{n-1}^{p+1} \\ T_n^{p+1} \end{Bmatrix} = \begin{Bmatrix} B_1 \\ B_2 \\ \vdots \\ \vdots \\ B_{n-1} \\ B_n \end{Bmatrix}$$

$$[A]\{T\} = \{B\}$$

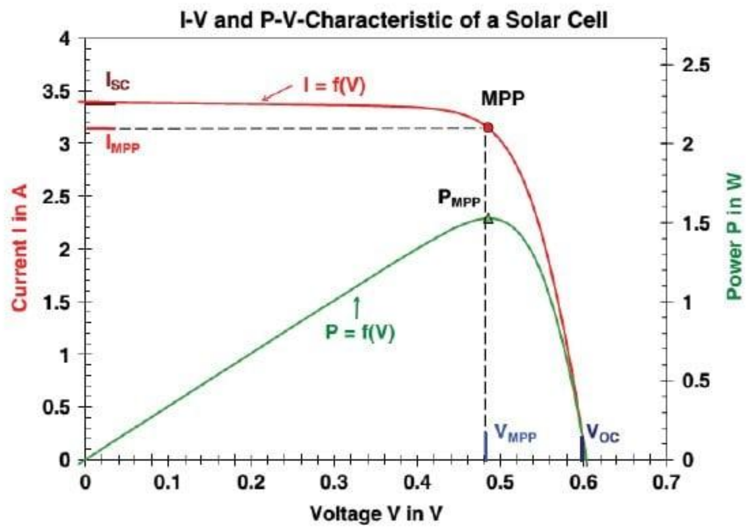
On the back surface of each module, four temperature sensors are arranged in a diagonal direction from the centre of the panel to the edge to verify temperature uniformity. The sensors are self-adhesive silicone rubber support with a thin film Pt100 Resistance Temperature Detector.

THERMAL MODELING OF PV PANELS

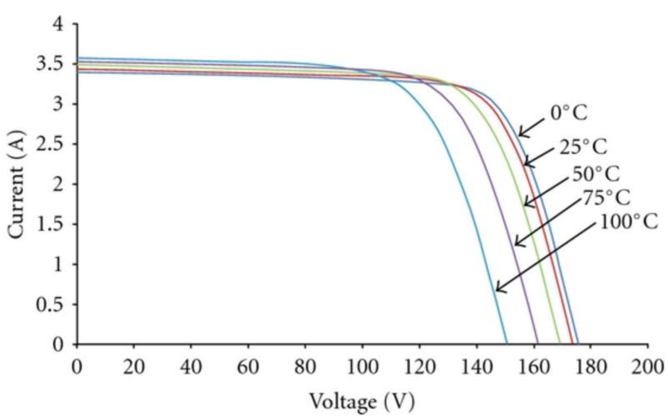


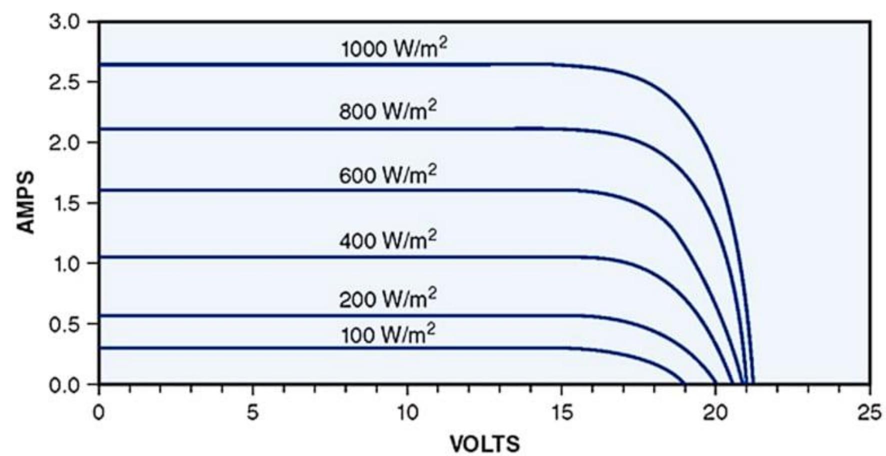
Season	RMSE (°C)	MBE (°C)	NSE	RMSE (W)	MBE (W)	NSE
Winter	1.49	0.0664	0.9818	4.19	0.0664	0.9950
Spring	1.35	0.0163	0.9903	4.33	-0.0422	0.9903
Summer	1.34	0.0015	0.9899	3.50	-0.0259	0.9973
Autumn	1.65	0.0037	0.9851	4.76	-0.0528	0.9945

COOLING OF PHOTOVOLTAIC PANELS



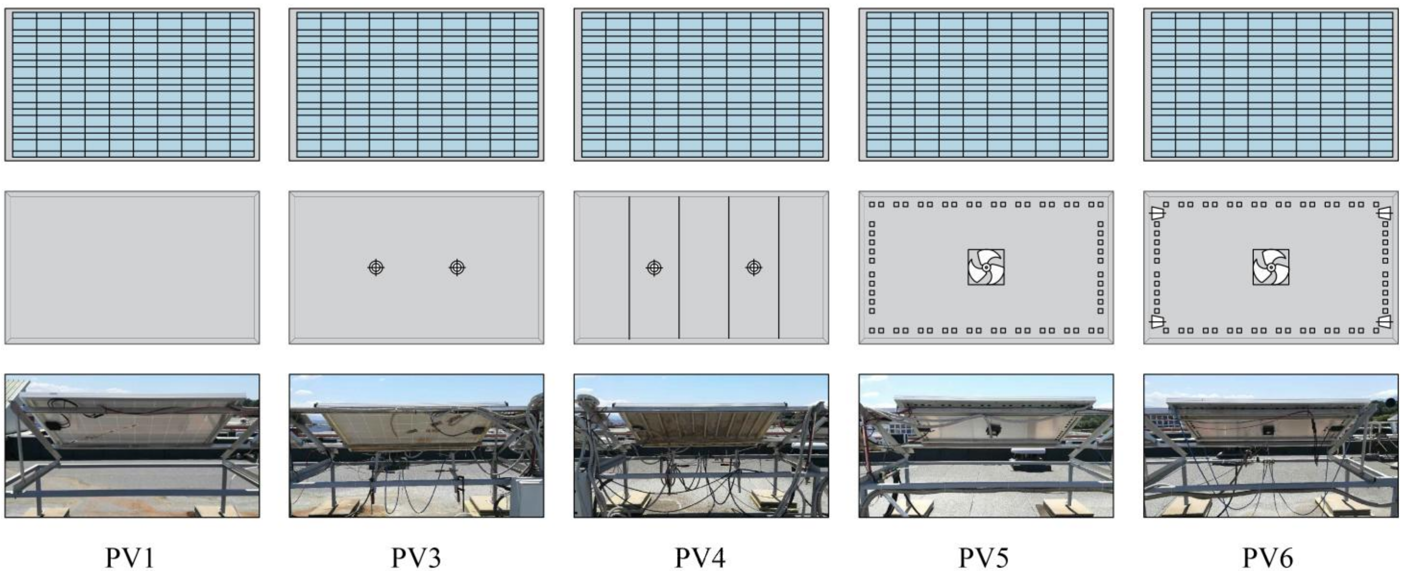
$$\eta = \eta_R \left[1 - \beta \left(T_c - T_R \right) + \gamma \log_{10} G \right]$$





COOLING OF PHOTOVOLTAIC PANELS

Module PV1 has no cooling system and is left as reference;
Module PV3 is equipped with two wide cone water spray nozzles
Module PV4 is equipped with the same two wide cone water spray nozzles but with the addition of a thin metallic panel fixed
Module PV5 is equipped with a ventilation system that produce forced convection
Module PV6 is similar to PV5 but with the addition of 4 spray nozzles.



COOLING OF PHOTOVOLTAIC PANELS

Module PV3

Module PV4

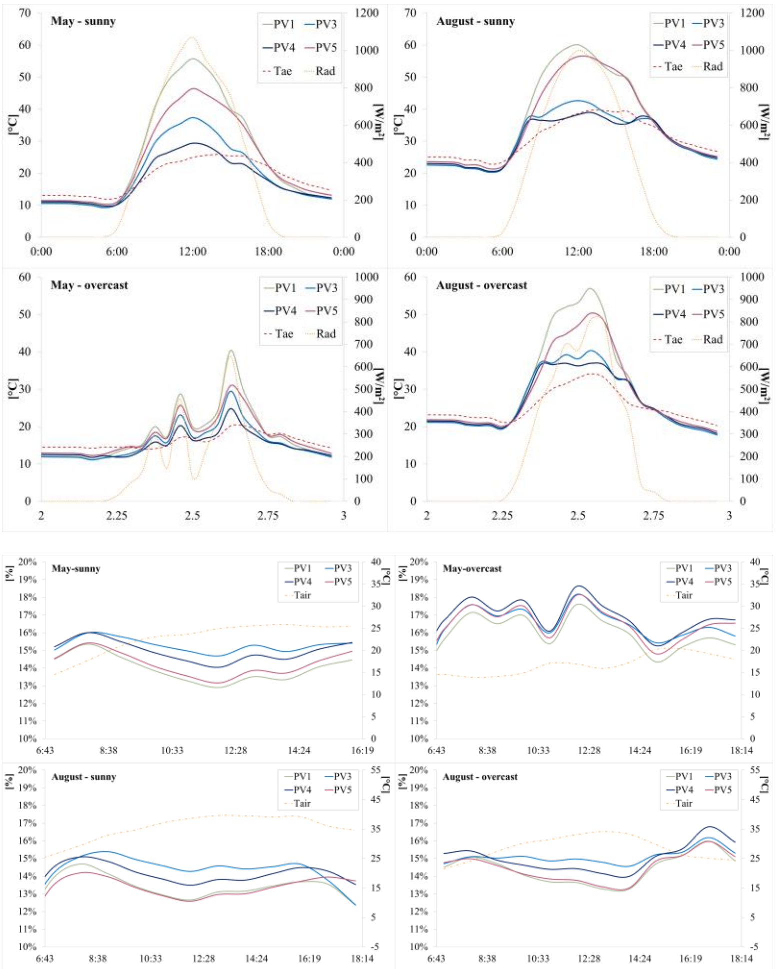
Module PV5

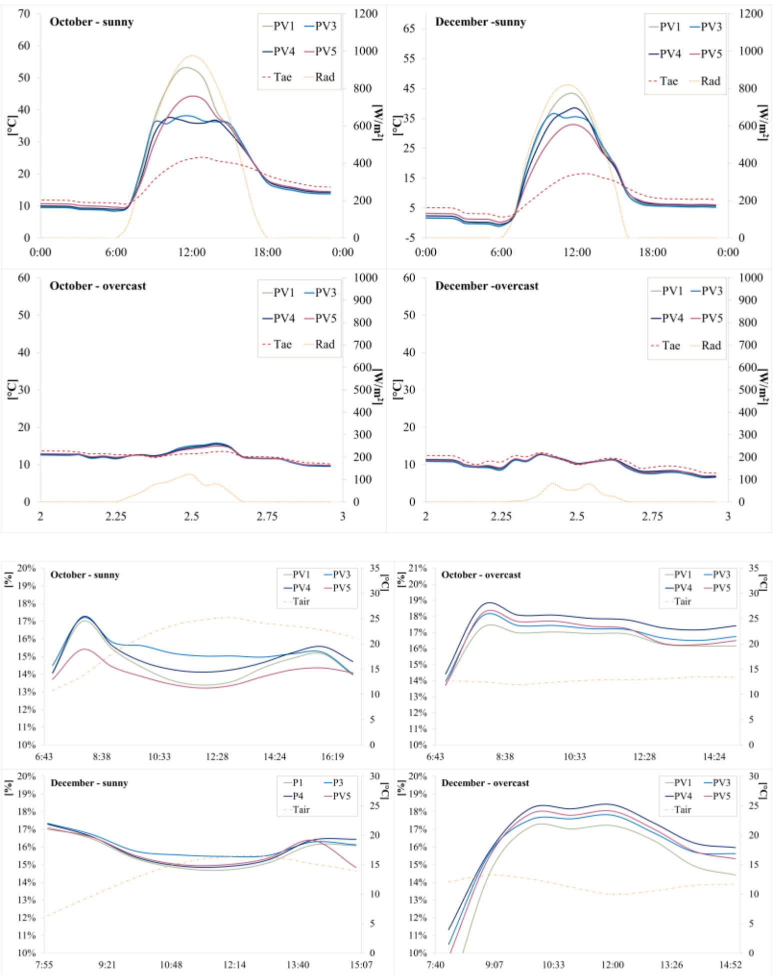
$$\eta = \frac{P_{el}}{A_{mod} \cdot G}$$

P_{el} is the DC electric power produced by the module [W];
A_{mod} is the net module area [m^2];
G is the global radiation on the tilted plane [W/m^2].

UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI INGEGNERIA MECCANICA, ENERGETICA E GESTIONALE

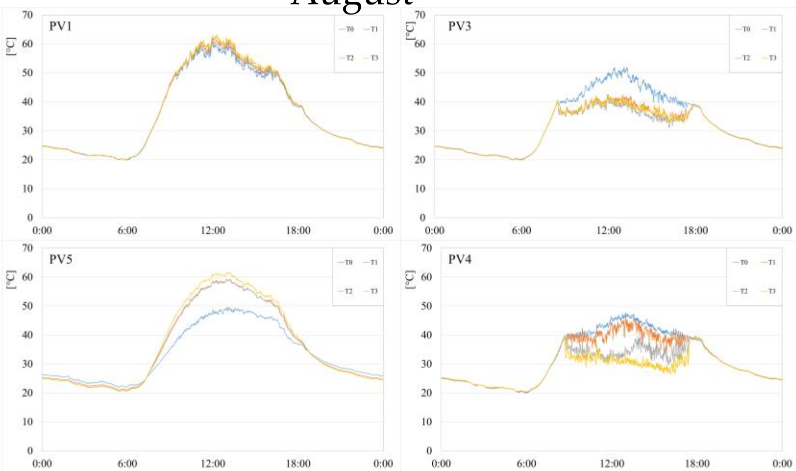
COOLING OF PHOTOVOLTAIC PANELS



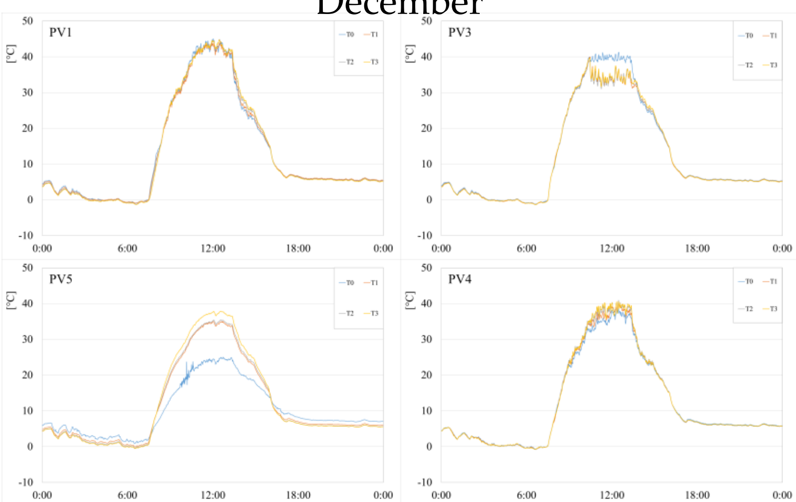


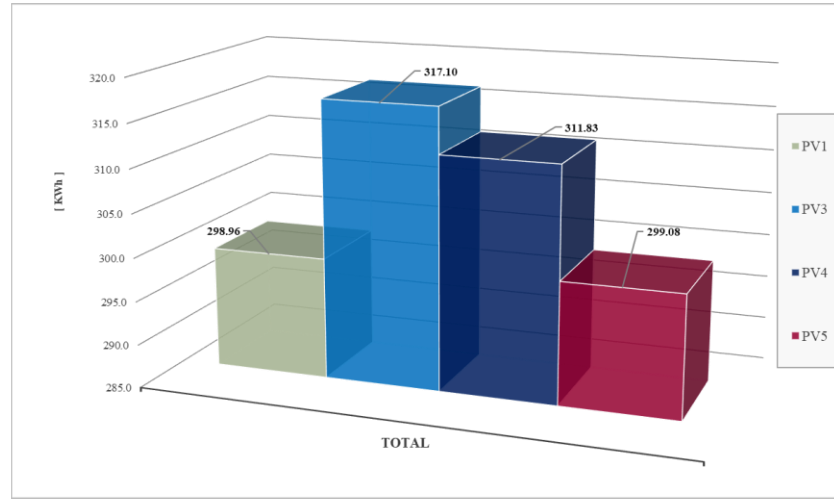
COOLING OF PHOTOVOLTAIC PANELS

August



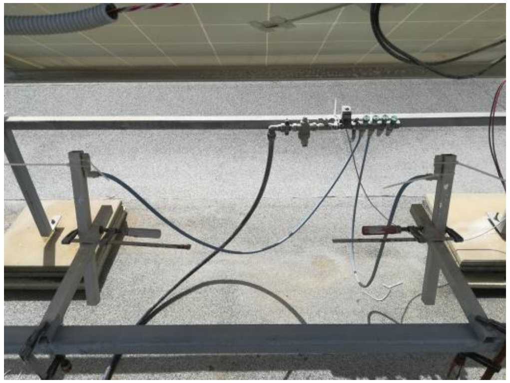
December

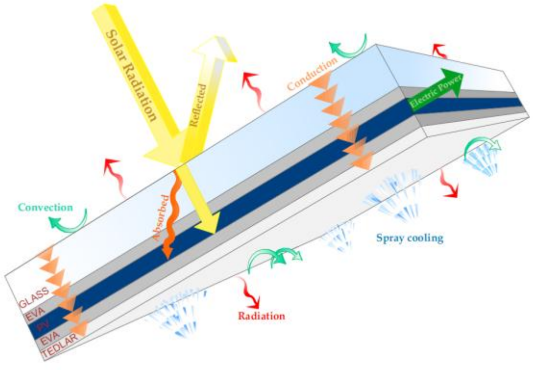




	PV1 [kWh]	PV3 [kWh]	PV4 [kWh]	PV5 [kWh]	ΔE1-3	ΔE1-4	ΔE1-5
April	40,34	43,37	42,58	40,92	7,5%	5,6%	1,4%
May	42,23	45,30	44,63	42,85	7,3%	5,7%	1,5%
June*	36,97	40,14	39,45	37,56	8,6%	6,7%	1,6%
July*	38,54	41,03	40,40	38,72	6,5%	4,8%	0,5%
August*	34,63	37,28	36,16	34,55	7,7%	4,4%	-0,2%
September	36,46	38,10	37,43	35,67	4,5%	2,7%	-2,2%
October	34,21	35,72	35,00	32,95	4,4%	2,3%	-3,7%
November	13,60	13,88	13,83	13,71	2,0%	1,7%	0,8%
December	21,98	22,28	22,35	22,15	1,4%	1,7%	0,8%

SPRAY COOLING MODELLING





Top node

Water mass and energy balance

$$m_{cool} = \dot{m}_{nozzle} * \Delta t_{spray} = n_{nozzle} * \rho_{wat} * u_{out} * A_{out} * \Delta t_{spray}$$

$$m_{cool,eff} = m_{cool} * \left(1 - \frac{PD}{100}\right)$$

$$m^{p}_{cool,eff} = m^{p-1}_{cool,eff} - m^{p-1}_{evap} - m^{p-1}_{drop}$$

$$\dot{m}^{p-1}_{evap} = \frac{(0{,}089 + 0{,}0782 \times u_a^{p-1}) * (p_w^{p-1} - p_a^{p-1})}{\lambda^{p-1}}$$

$$\dot{E}_{cooling} = \dot{E}_{sens} + \dot{E}_{lat} = cp_{water} \times \dot{m}_{cool,eff} \times \left(T_m^{p+1} - T_{water}^{p+1}\right) + \lambda_{lat} \times \dot{m}_{evap}$$

UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI INGEGNERIA MECCANICA, ENERGETICA E GESTIONALE

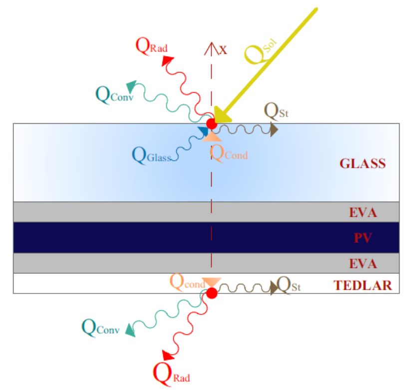
SPRAY COOLING MODELLING

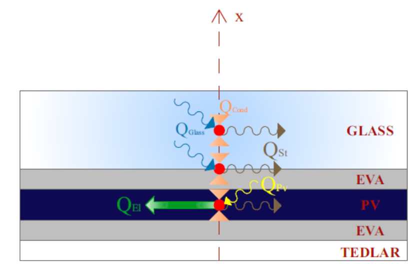
Top node

$$\dot{\mathbf{E}}_{\mathbf{in}} = \mathrm{k}_{\mathrm{gl}}\left(\frac{\mathrm{T}_{\mathrm{m-1}}^{\mathrm{p+1}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}}{\Delta \mathrm{x}}\right) + \mathrm{h}_{\mathrm{conv}}\left(\mathrm{T}_{\mathrm{air}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}\right) + \mathrm{h}_{\mathrm{rad,gl-sky}}\left(\mathrm{T}_{\mathrm{sky}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}\right) + \mathrm{h}_{\mathrm{rad,gl-ground}}\left(\mathrm{T}_{\mathrm{ground}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}\right)$$

$$\dot{\mathbf{E}}_{\mathbf{g}} = \dot{Q}_{gl}\frac{\Delta \mathrm{x}}{2}$$

$$\dot{\mathbf{E}}_{\mathbf{st}} = \left(\rho_{\mathrm{gl}} \cdot \mathrm{c}_{\mathrm{gl}} \cdot \frac{\Delta \mathrm{x}}{2}\right)\left(\frac{\mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p}}}{\Delta \mathrm{t}}\right)$$





Bottom node

$$\dot{\mathbf{E}}_{\mathbf{in}} = \mathrm{k}_{\mathrm{ted}} \cdot \left(\frac{\mathrm{T}_{\mathrm{m+1}}^{\mathrm{p+1}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}}{\Delta \mathrm{x}}\right) + \mathrm{h}_{\mathrm{conv}} \cdot \left(\mathrm{T}_{\mathrm{amb}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}\right) + h_{\mathrm{rad,ted-sky}} \cdot \left(\mathrm{T}_{\mathrm{sky}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}\right) + \mathrm{h}_{\mathrm{rad,gl-ground}} \cdot \left(\mathrm{T}_{\mathrm{ground}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}}\right) - \left(cp_w \cdot G_{film} \cdot \left(T_m^{p+1} - T_w^{p+1}\right) + \lambda_{lat} \cdot \dot{m}_{evap}\right)$$

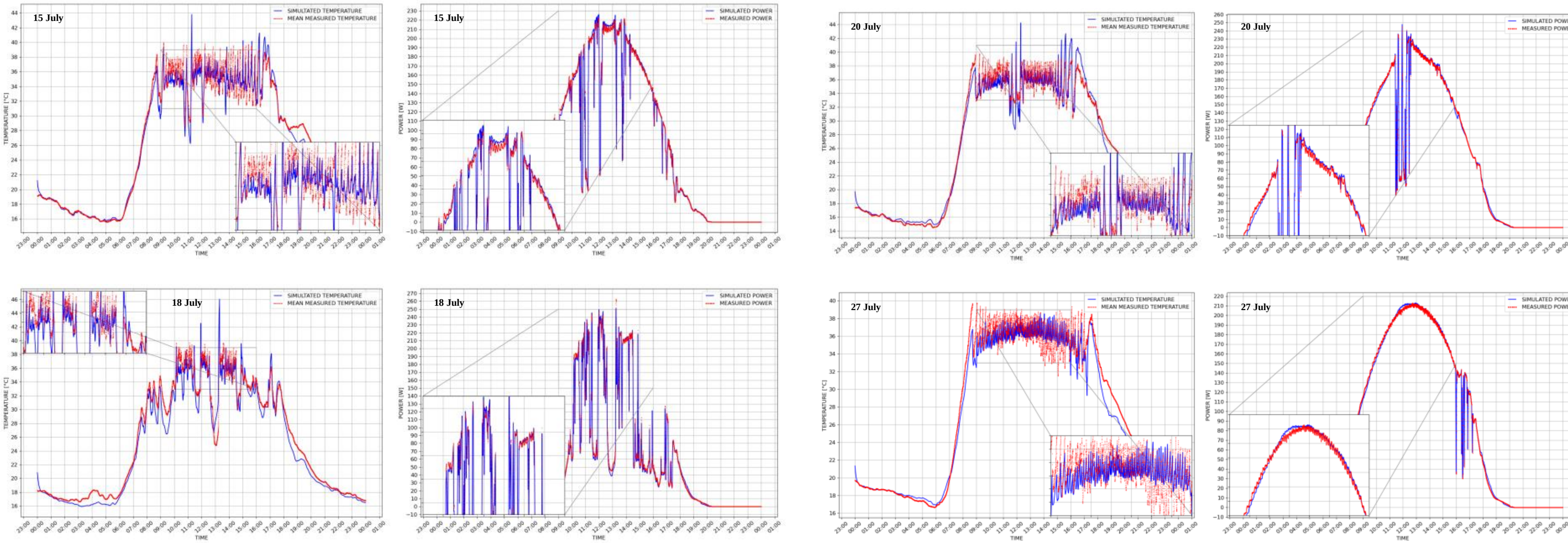
$$\dot{\mathbf{E}}_{\mathbf{g}} = 0$$

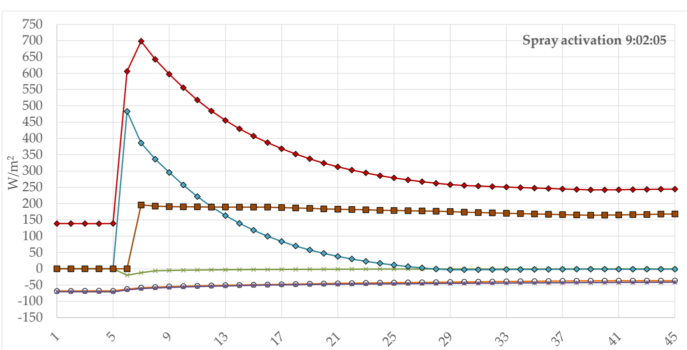
$$\dot{\mathbf{E}}_{\mathbf{st}} = \left(\rho_{\mathrm{ted}} \cdot \mathrm{c}_{\mathrm{ted}} \cdot \frac{\Delta \mathrm{x}}{2}\right)\left(\frac{\mathrm{T}_{\mathrm{m}}^{\mathrm{p+1}} - \mathrm{T}_{\mathrm{m}}^{\mathrm{p}}}{\Delta \mathrm{t}}\right)$$

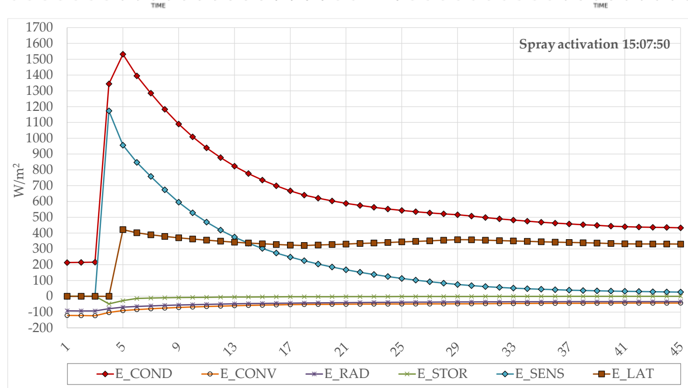
UNIVERSITÀ DELLA CALABRIA

UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO DI INGEGNERIA MECCANICA, ENERGETICA E GESTIONALE

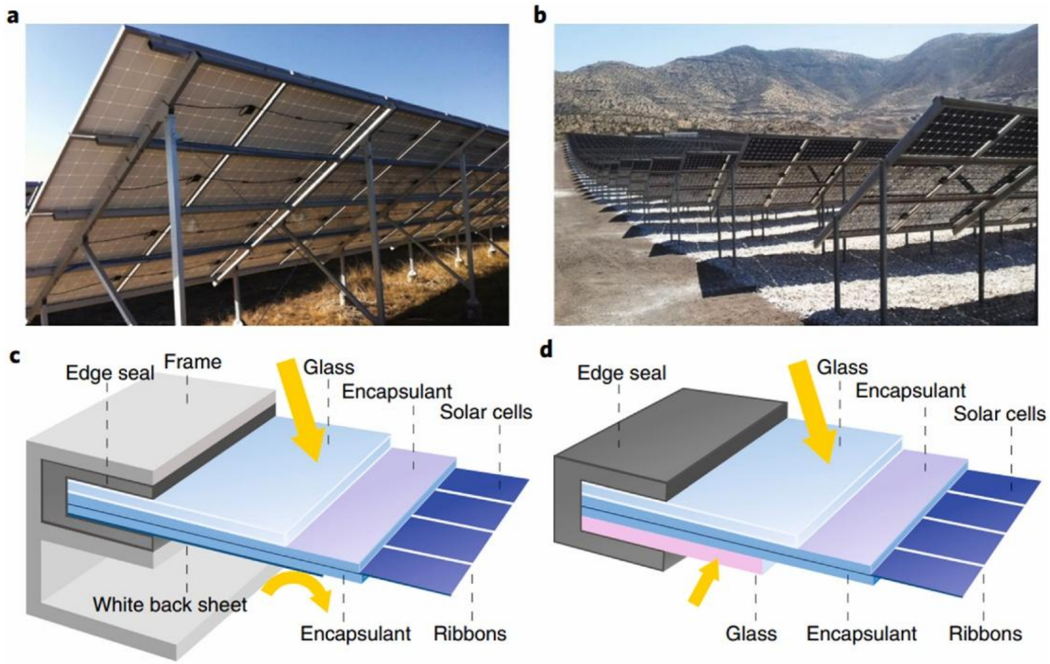
SPRAY COOLING MODELLING







BIFACIAL PV MODELLING



A bifacial photovoltaic module (bPV) is another type of photovoltaic module in which, instead of an opaque and non-transparent backsheet as in the monofacial photovoltaic module (mPV), a rear glass is installed to allow sunlight coming from the rear side of the module to reach the solar cell and generate electricity.The increase in production in the bifacial module up to 30% compared to the monofacial module is the result of utilizing the rear side of the module, converting the radiation reflected from the ground due to albedo."

BIFACIAL PV MODELLING

The measurement of this IV curve, in natural or simulated sunlight, but applied to photovoltaic bifacial modules, adheres to the technical specification IEC TS 60904-1-2:2019.
Consequently, each bifacial module should inherently exhibit three fundamental values: bifaciality coefficient of Isc (φ_{Isc}), Voc (φ_{Voc}) and Pm (φ_{Pmax}), respectively.
Nevertheless, manufacturers mostly indicate solely the corresponding coefficient concerning the ratio between maximum powers of both sides (φ_{Pmax}) ((IEC) International Electrotechnical Commission, 2021c).
The majority of the manufacturers only use the STC maximum power of the front side, as prescribed by the IEC 61724–1:2021.
The current models utilize the static bifaciality measured under standard test conditions (STC: 1000 W/m2, module temperature 25 ◦C, air mass 1.5 spectra) to convert the irradiance intensity on the front and rear sides into equivalent irradiance intensity, and further calculates the output power of bPV module. The equivalent irradiance intensity (G_E) is calculated as follows:

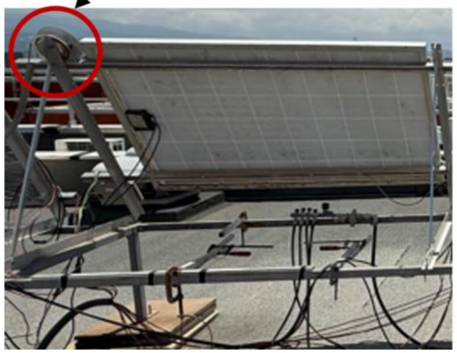
$$G_E = G_F + \varphi_{stc} G_R$$

Where GF and GR are the irradiance intensity on the front and the rear sides of the module. φstc is the static bifaciality under STC.

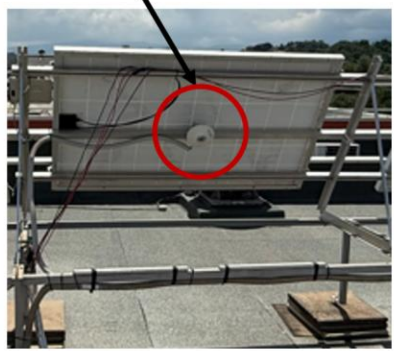
UNIVERSITÀ DELLA CALABRIA

BIFACIAL PV MODELLING

Front pyranometer

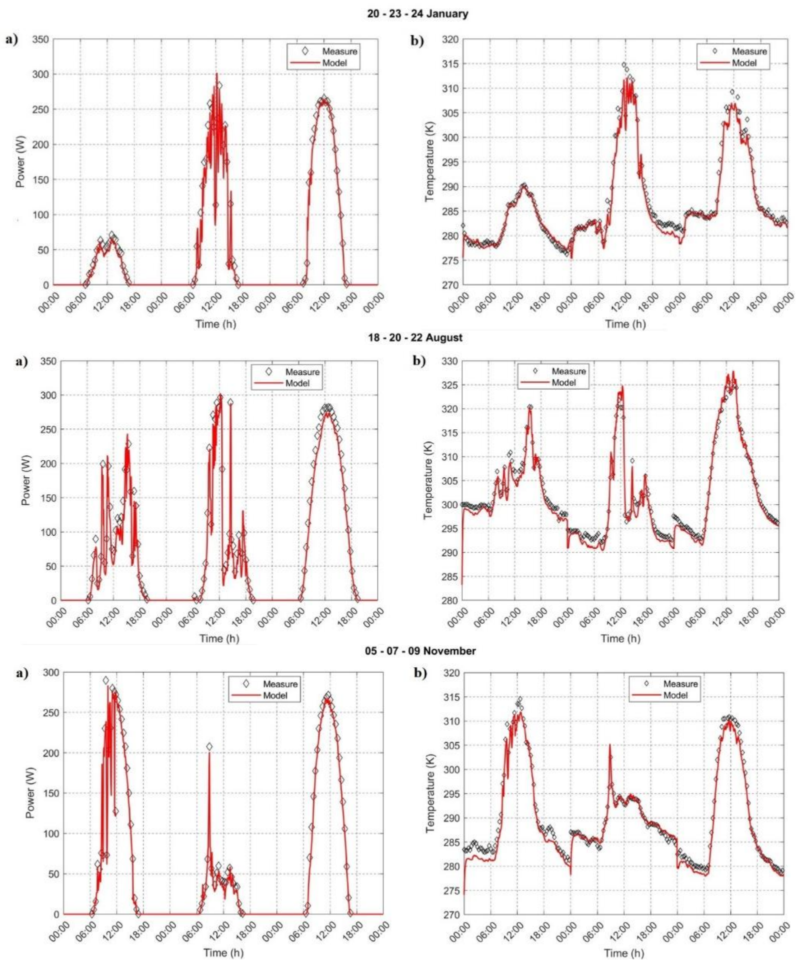


Rear pyranometer



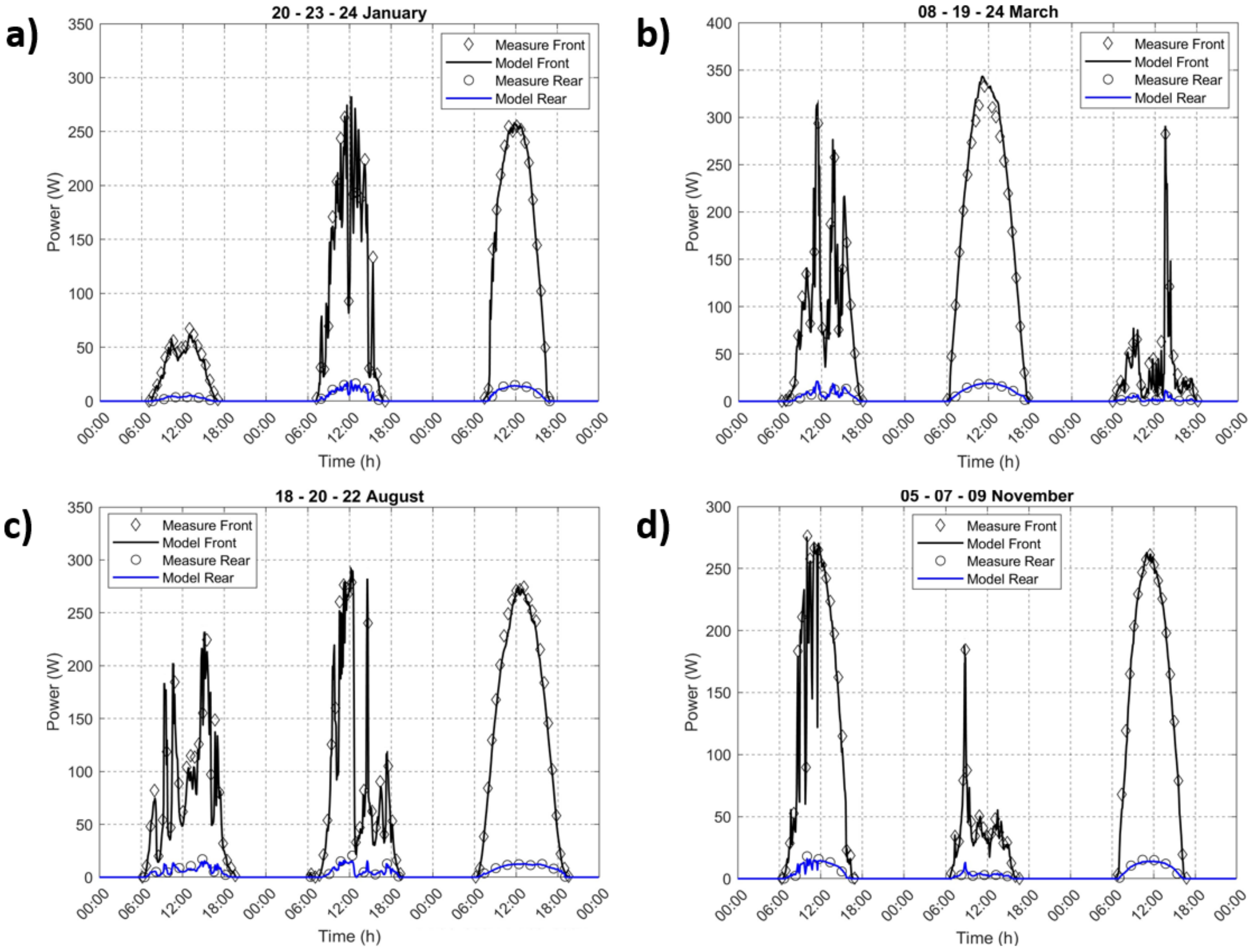
PV1 PV2 PV3

BIFACIAL PV MODELLING

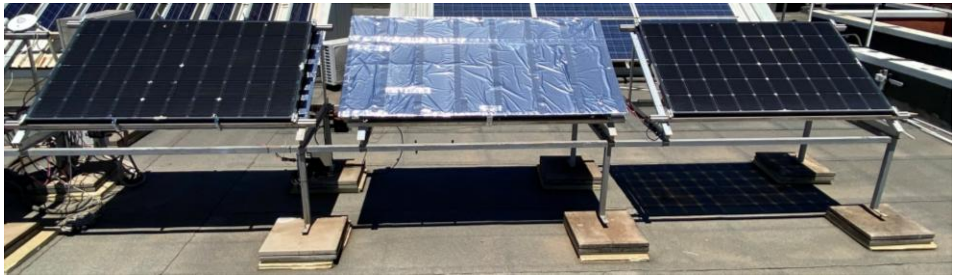


Identifier	RMSE (W)	R^2 (-)	MAE (W)	Identifier	RMSE (W)	R^2 (-)	MAE (W)
Jan-A	4.01	0.9728	2.35	July-A	9.37	0.9894	6.19
Jan-B	6.17	0.9943	3.89	July-B	8.02	0.9894	6.91
Jan-C	4.33	0.9982	2.24	July-C	10.05	0.9841	8.23
Feb-A	4.31	0.9986	2.37	Aug-A	9.56	0.9757	7.14
Feb-B	4.17	0.9923	2.46	Aug-B	7.72	0.9916	4.88
Feb-C	4.88	0.9973	2.60	Aug-C	8.11	0.9901	6.52
Mar-A	5.96	0.9938	3.17	Sep-A	7.63	0.9758	4.61
Mar-B	10.48	0.9905	6.10	Sep-B	8.09	0.9897	4.73
Mar-C	4.18	0.9878	2.62	Sep-C	8.71	0.9938	5.50
Apr-A	8.71	0.9879	5.69	Oct-A	6.45	0.9935	3.27
Apr-B	4.91	0.9451	3.31	Oct-B	9.24	0.9899	5.71
Apr-C	7.14	0.9949	4.13	Oct-C	10.07	0.9894	6.33
May-A	7.48	0.9944	4.64	Nov-A	5.43	0.9969	3.06
May-B	7.52	0.9919	5.05	Nov-B	3.97	0.9815	2.30
May-C	5.48	0.9688	3.53	Nov-C	5.92	0.9966	3.27
June-A	8.50	0.9981	6.47	Dec-A	3.14	0.9920	1.66
June-B	11.38	0.9730	9.10	Dec-B	5.41	0.9972	2.84
June-C	8.08	0.9731	6.98	Dec-C	4.64	0.9978	2.63

BIFACIAL PV MODELLING

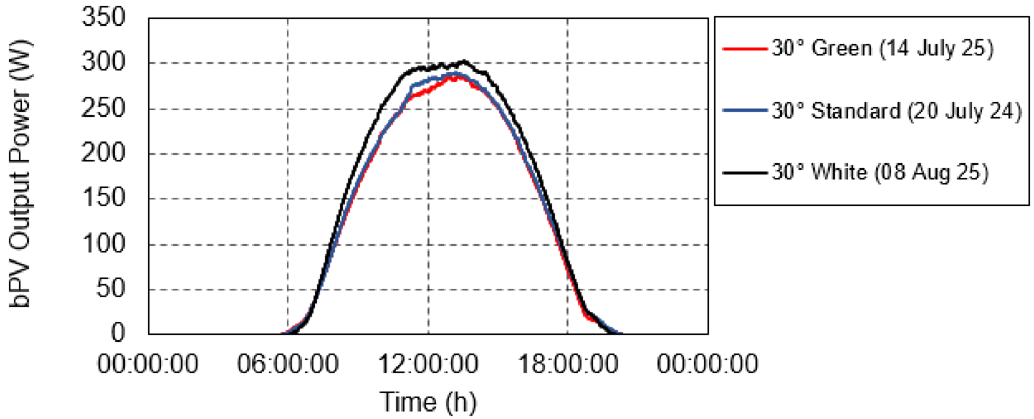


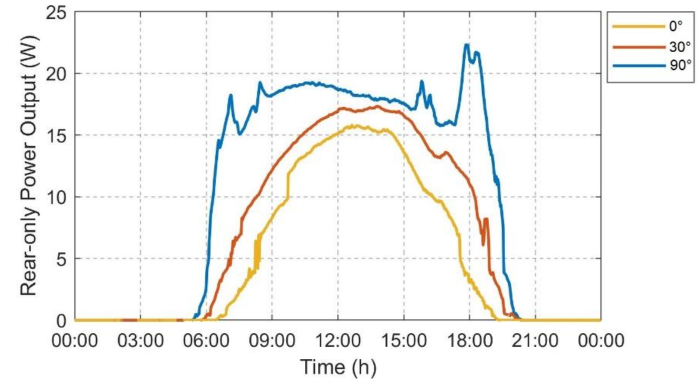
BIFACIAL PV EXPERIMENTAL

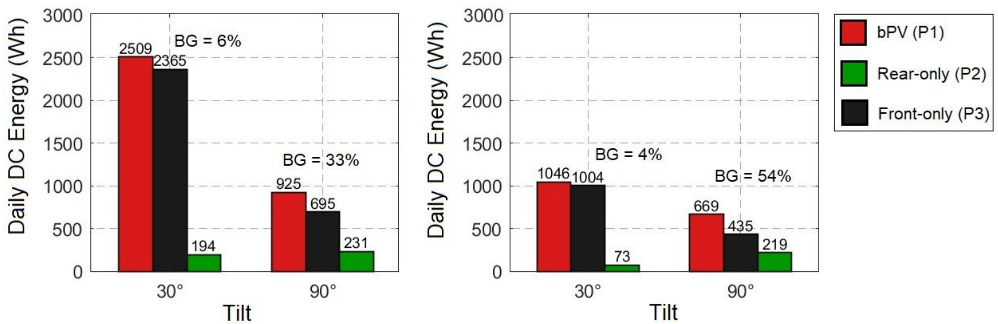


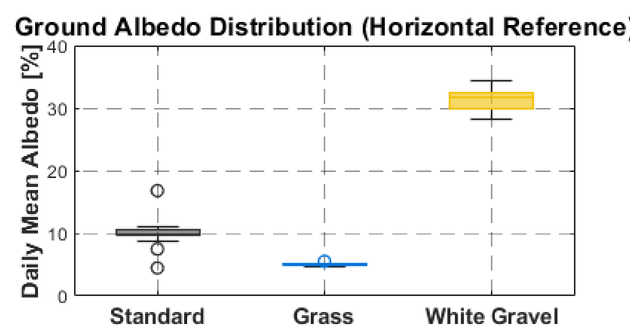
BIFACIAL PV EXPERIMENTAL

BIFACIAL PV EXPERIMENTAL









THANK YOU FOR YOUR ATTENTION!

piero.bevilacqua@unical.it