Experience from PV system performence including comparison of on-roof and façade systems.
(Case study on BIPV systems.)

Vitezslav Benda
CTU Prague, Faculty of Electrical Engineering

KATEDRA ELEKTROTECHNOLOGIE FEL PRAHA

Intelligent energy management in the household

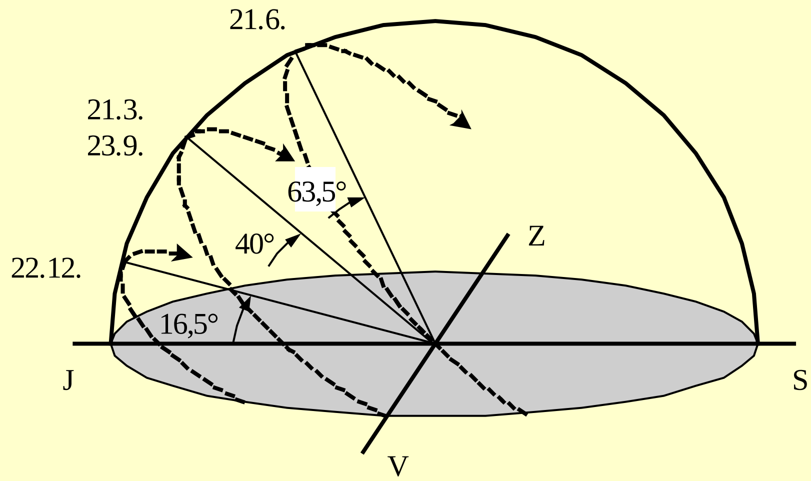
„Zero energy“ house cannot operate without PV system

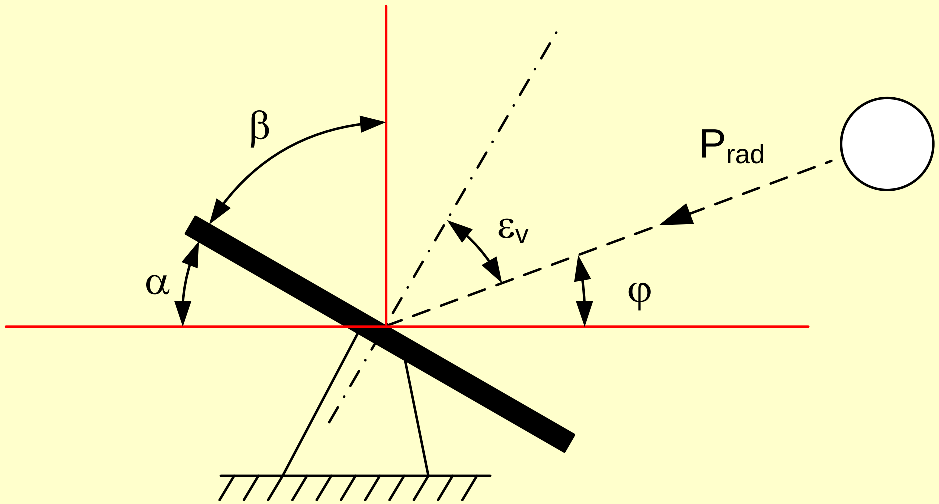
PV systems may be integrated into building construction

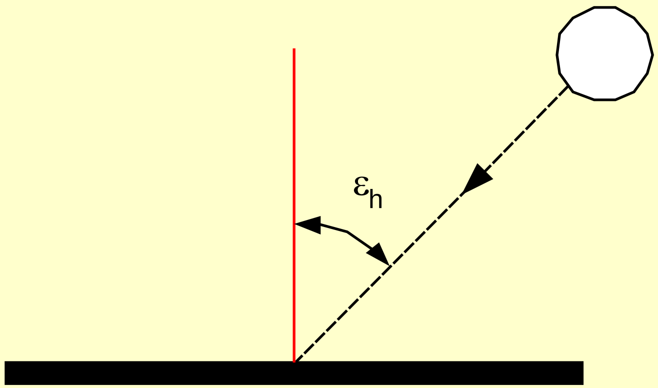
PV system output power depens on

- **Irradiance**

•Operating temperature





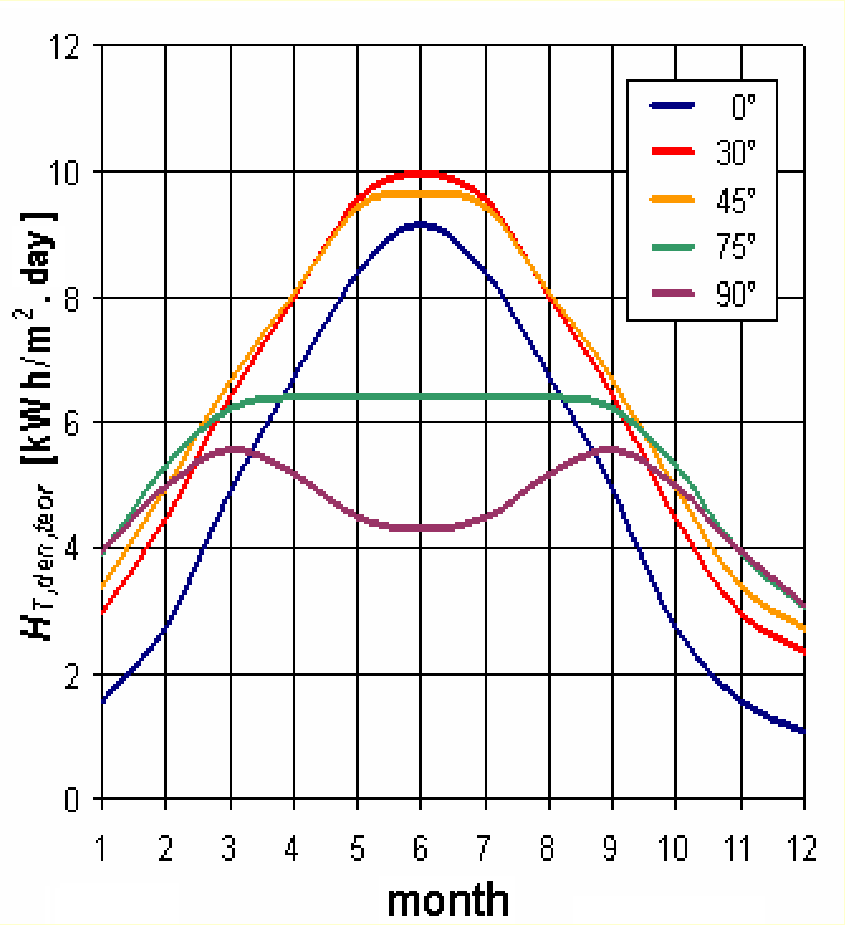


$$B(t) = 1367 \times 0.7^{\frac{1}{\sin\varphi(t)}} \cos\varepsilon_v(t) \cos\varepsilon_h(t)$$

$$W_u = \int_{SR}^{SS} 1367 \times 0.7^{\frac{1}{\sin\varphi(t)}} \cos\varepsilon_v(t) \cos\varepsilon_h(t) dt$$

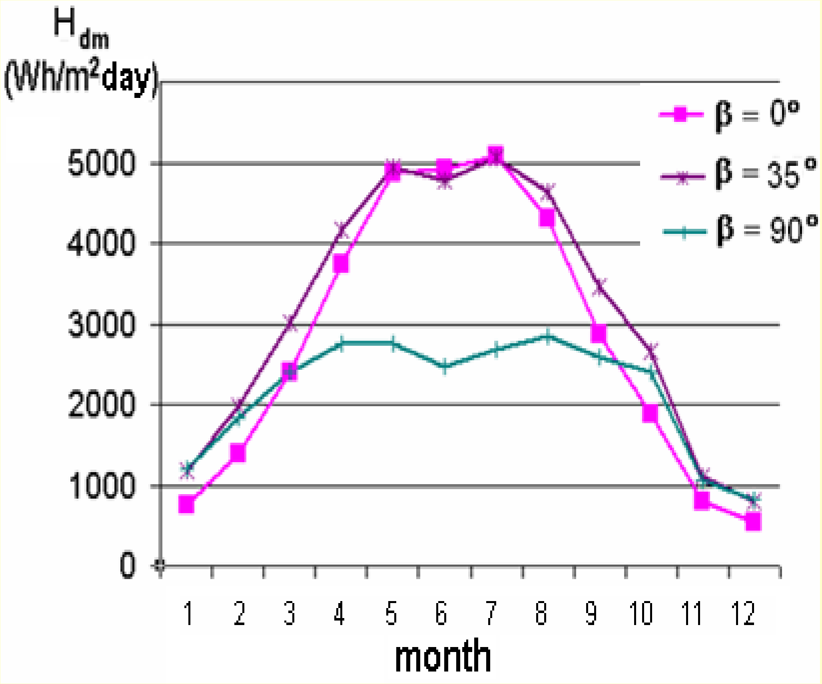
Radiation arriving on PV module

Clear sky

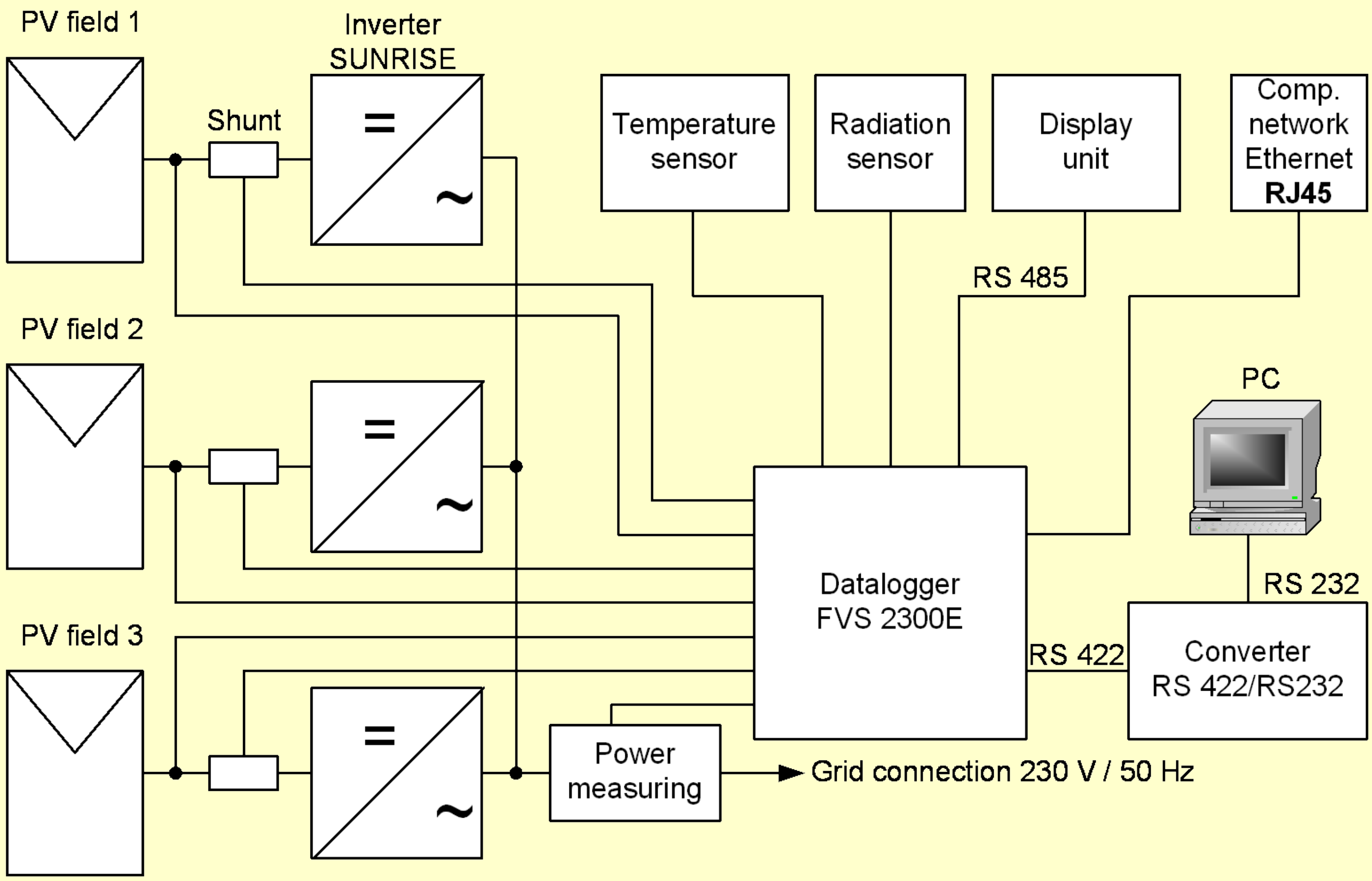


Cloudy sky increases portion of diffuse radiation

Reality:

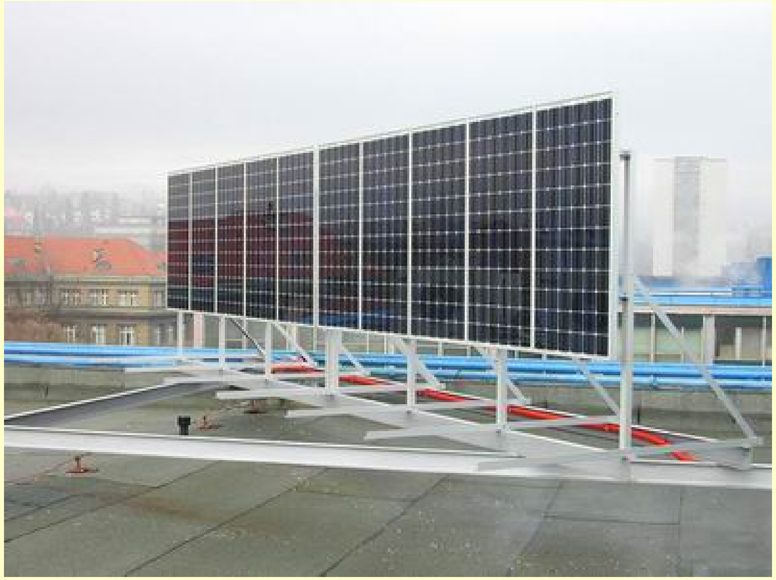


In the year 2001, a 3kW$_p$ demonstration, on-grid connected photovoltaic system has been built at the Czech Technical University in Prague on the roof of the Faculty of Electrical Engineering.



Installed peak power: 3320 W_p
Total module area: 26 m^2
Number of modules: 30 (3 fields of 10)
Latitude: 50.07 °N
Altitude: 205 m

http://andrea.feld.cvut.cz/FVS

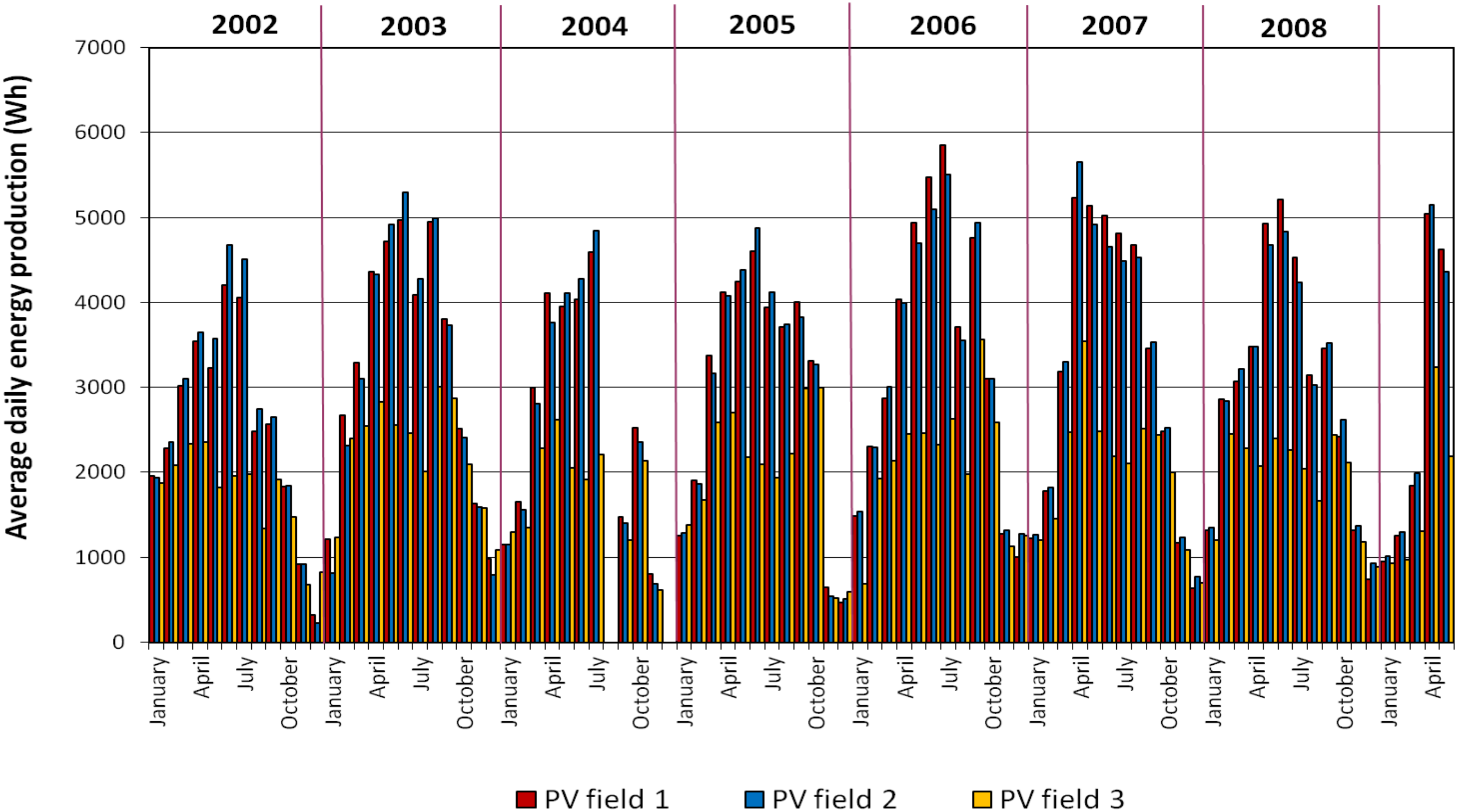


PV field	Tilt angle	Module type	P_m (W_p)
1	45°	RADIX72-112	1120
2	variable	RADIX72-112	1120
3	90°	RADIX72-108	1080

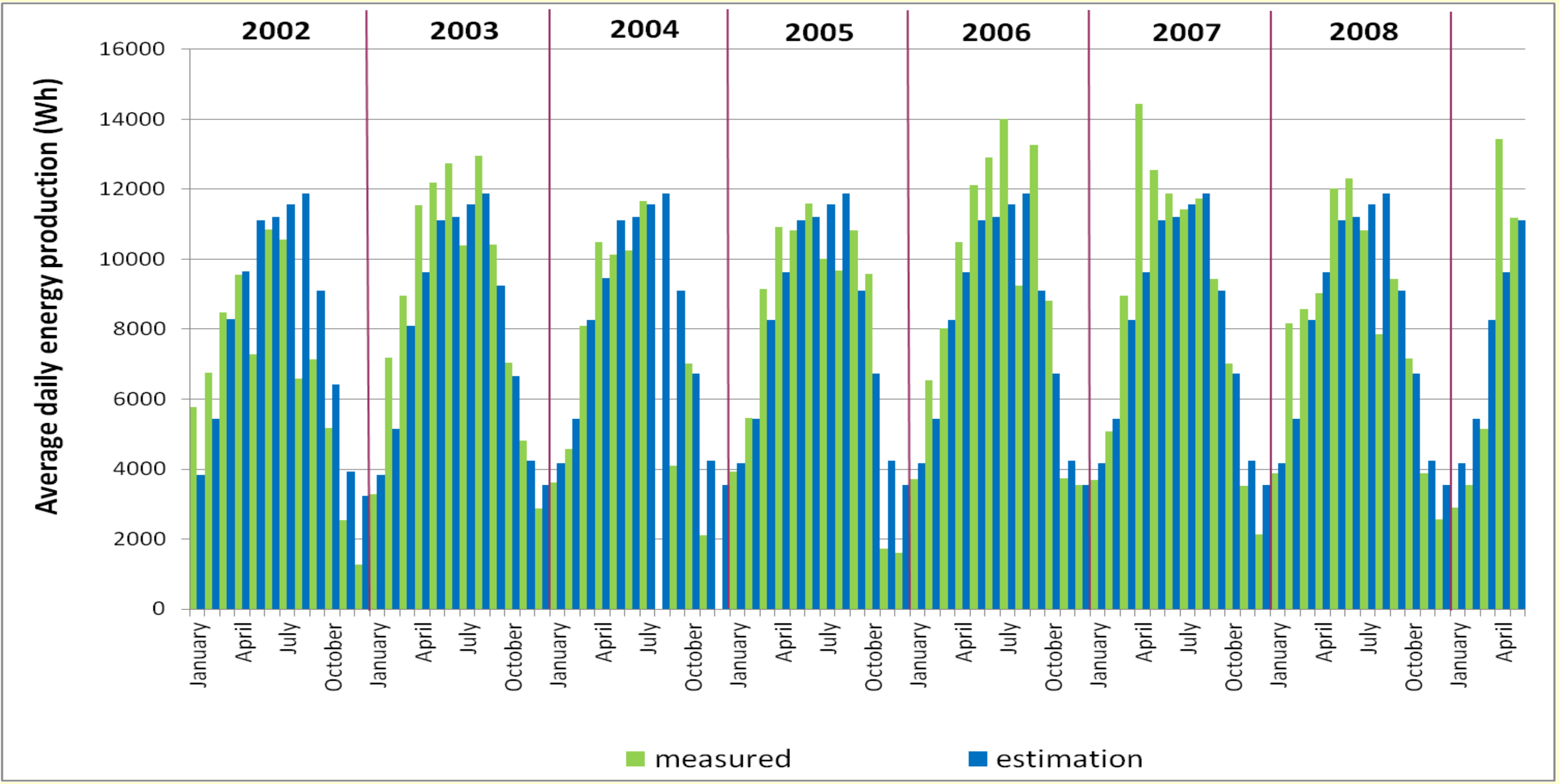
Parameters of individual PV fields

Inverters: Fronius Sunrice Mini

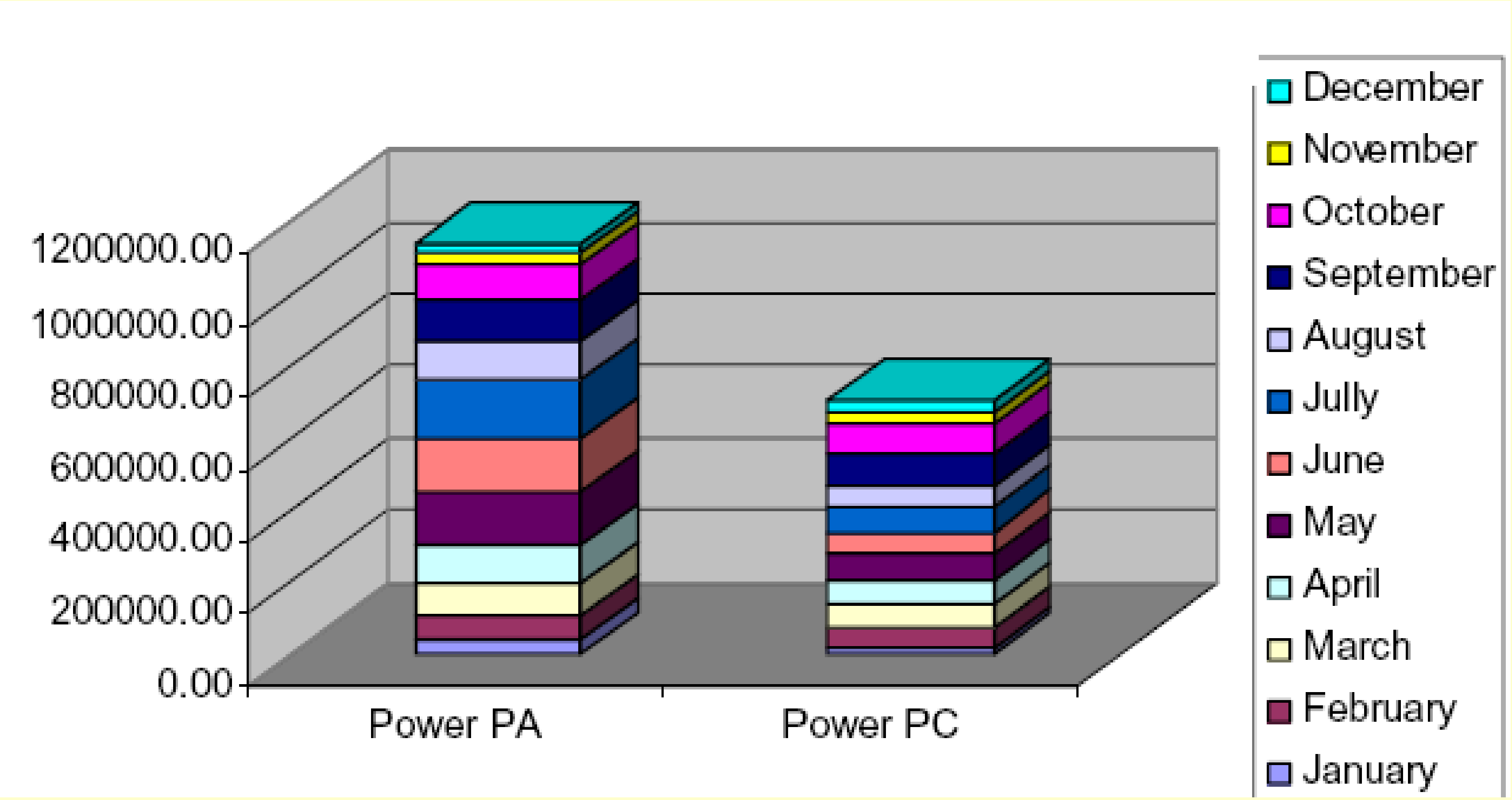
Energy produced by individual PV fields in period from January 2002 to May 2009



A comparison of estimated and measured energy production in period from January 2002 to May 2007



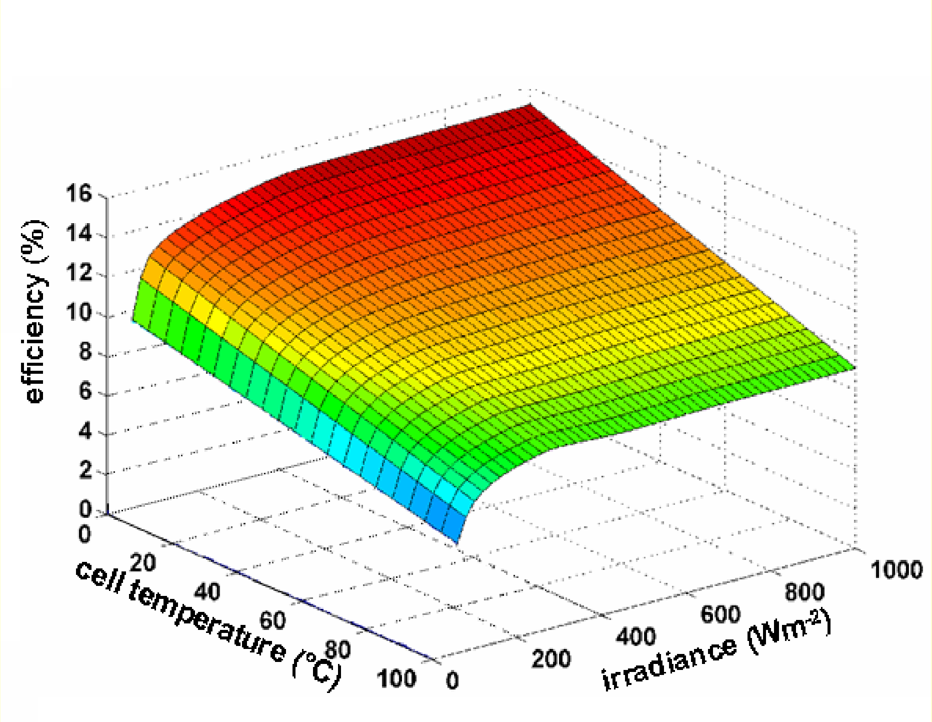
Comparison of on-roof and façade PV field in the year 2006



The module efficiency depends on irradiance and solar cell operating temperature

Both fill factor and efficiency

decrease with temperature

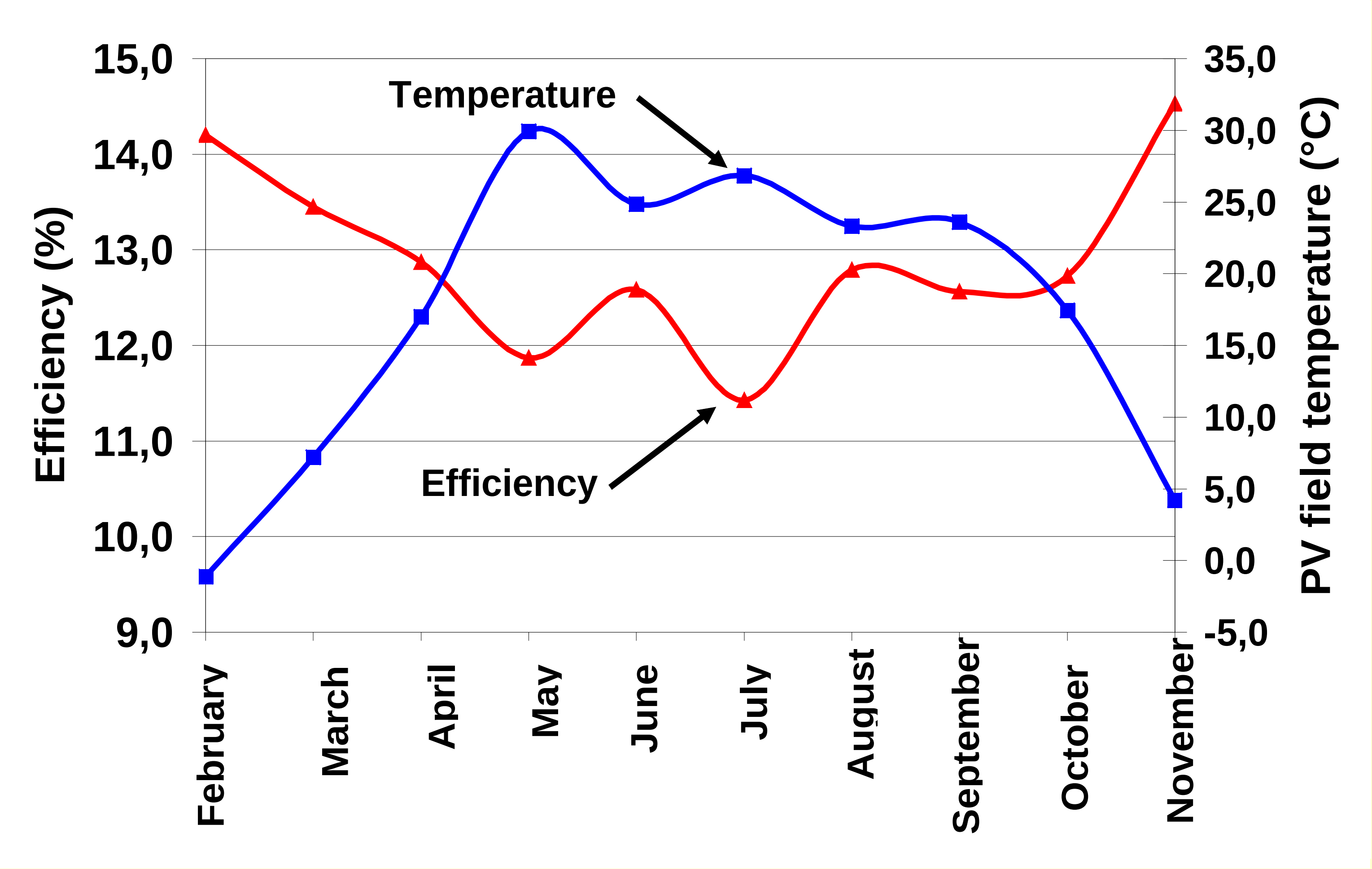


$$\frac{\partial FF}{\partial T} < 0 \qquad \frac{\partial \eta}{\partial T} < 0$$

At crystalline silicon cells

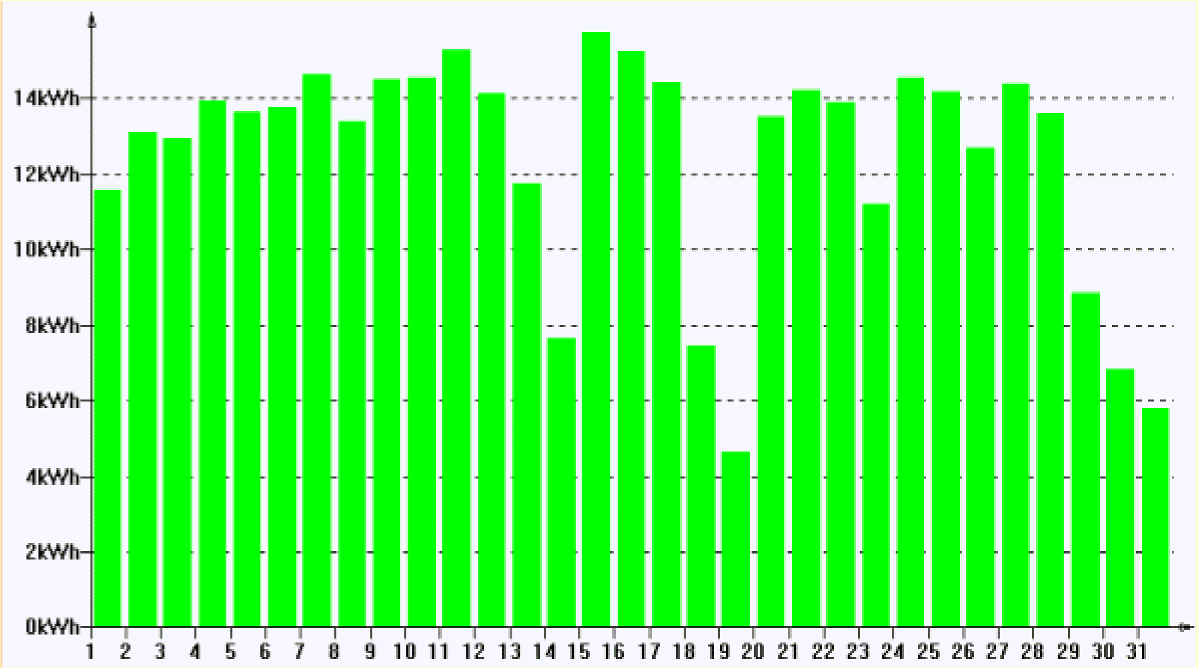
$$\frac{1}{\eta}\frac{\partial \eta}{\partial T} \approx 0.5\% K^{-1}$$

Temperature dependece of energy conversion efficiency

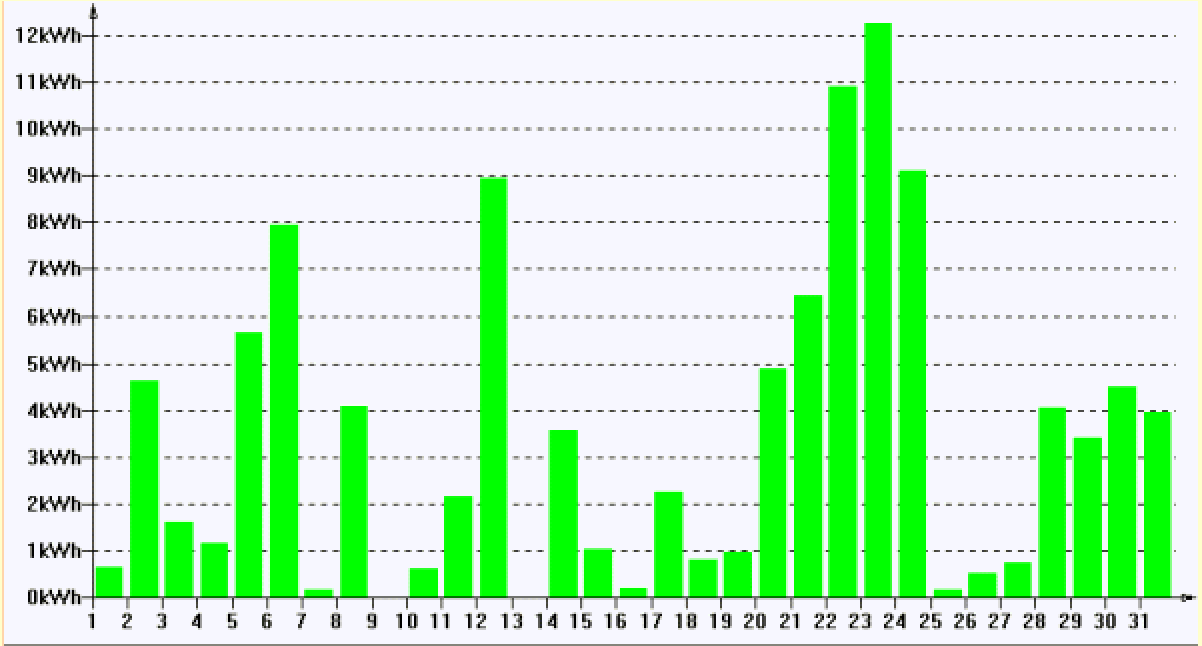


This gives the efficiency decrease of about 0.6% per 1K, which is higher than supposed decrease of cell efficiency (about 0.4% per 1K).

It means that an increase of losses with increasing temperature in other parts of system cannot be neglected.

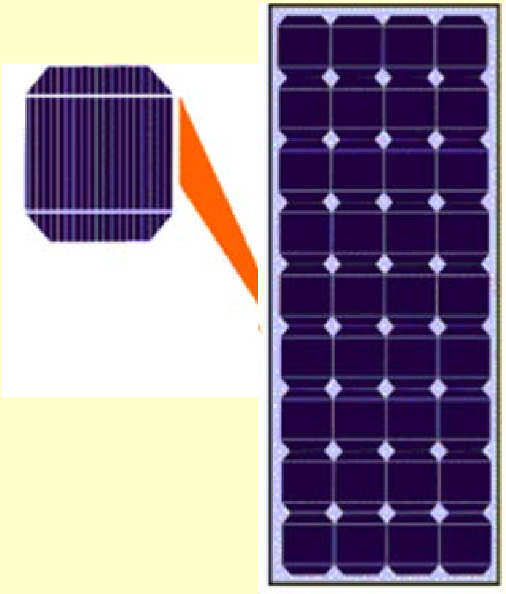


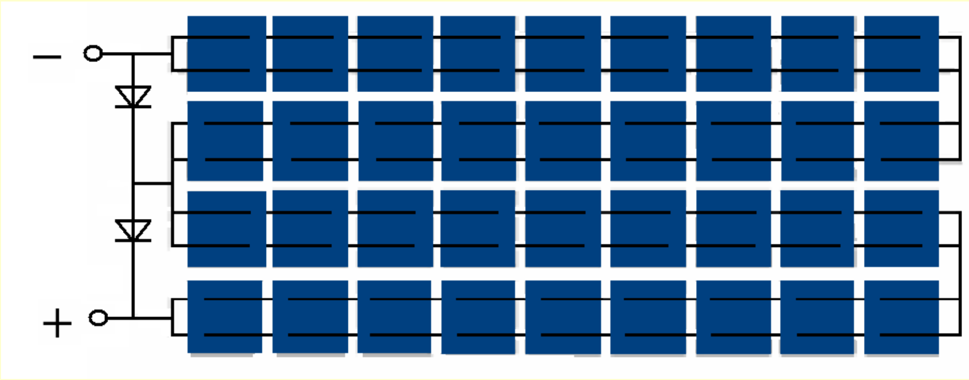
August



January

PV modules



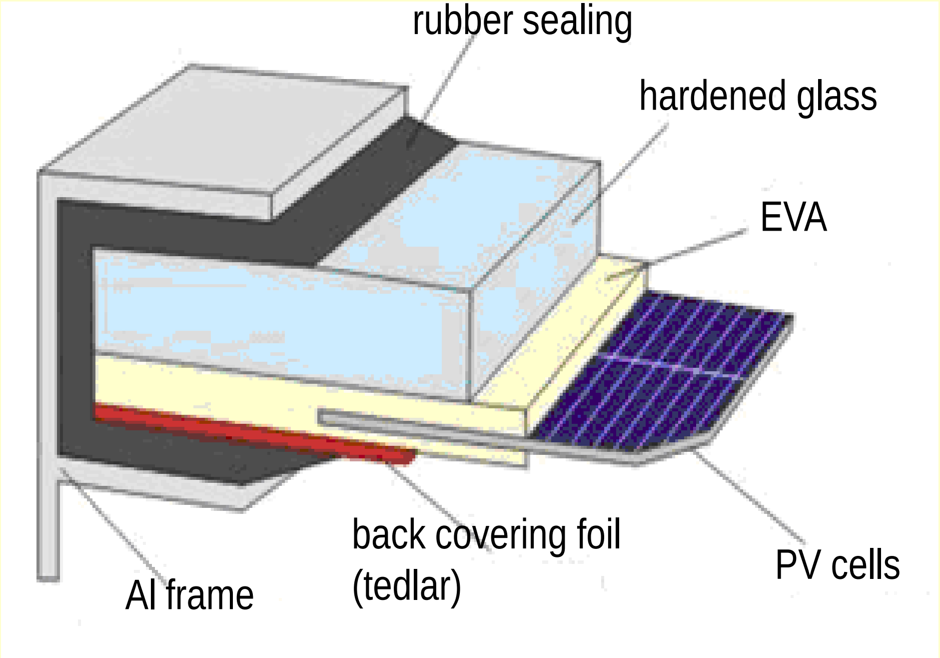


Cell operating temperature

$$T_c = T_a + r_{thca} G_{ab}$$

$$r_{\text{thca}} = \frac{r_{\text{thcaf}} r_{\text{thcab}}}{r_{\text{thcaf}} + r_{\text{thcab}}}$$

$$r_{thcaf} = \frac{d_f}{\lambda_f} + \frac{1}{h_f} \qquad r_{thcab} = \frac{d_b}{\lambda_b} + \frac{1}{h_b}$$



Module temperature $\boldsymbol{T_{mod}}$ can be measured on the rear of the module

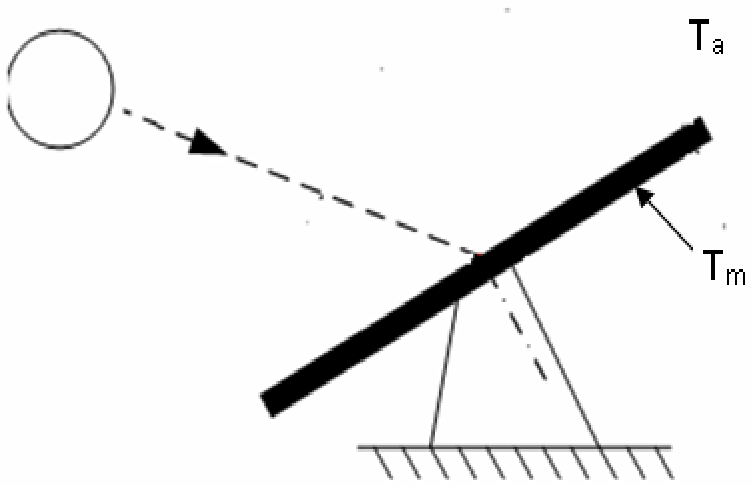
$$T_c = T_{\text{mod}} + \Delta T \frac{G}{G_{SCT}}$$

Influence of temperature

Open circuit voltage V_{OC} depends on the cell temperature T_c

$$V_{OC}(T_c) = V_{OC}^* + (T_c - T_c^*)\frac{dV_{OC}}{dT_c}$$

$$T_c = T_m + \frac{G_{eff}}{G^*}\Delta T$$



Temperature of the back surface T_m

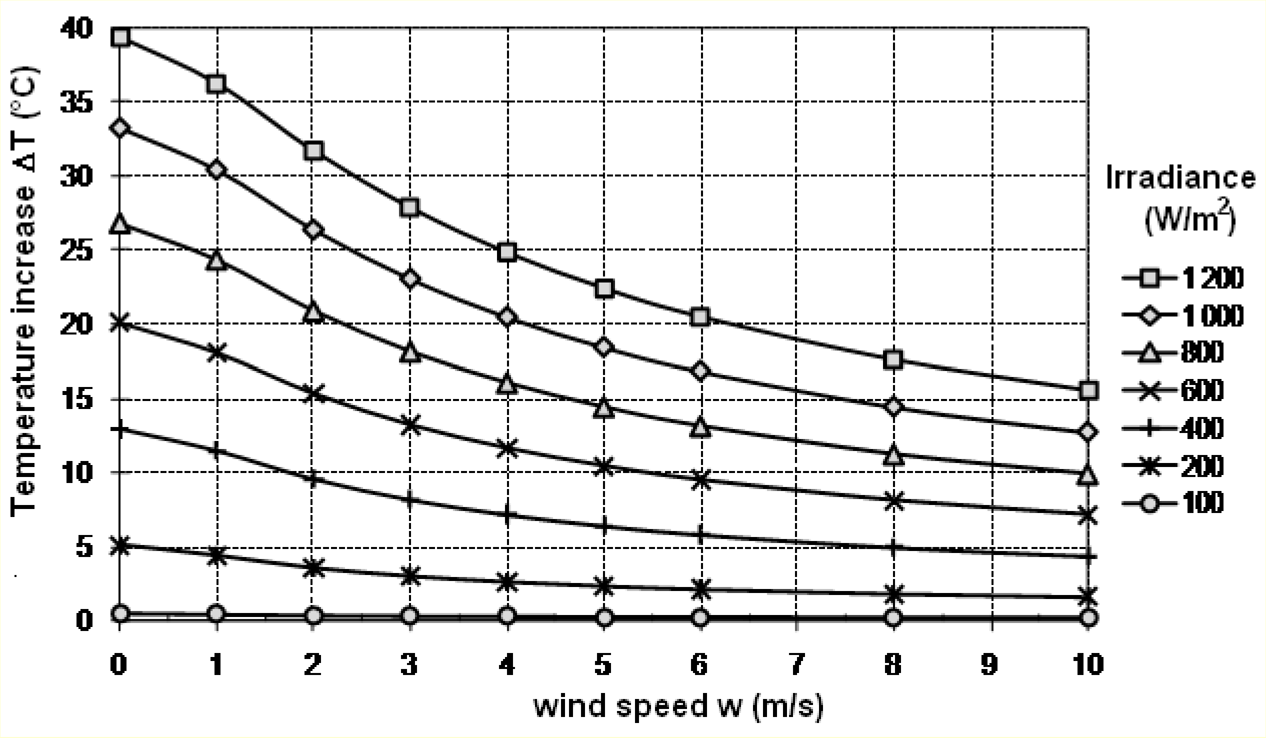
$$T_m = T_a + \frac{G_{eff}}{G^*}\left[T_1 \exp(b v_W) + T_2\right]$$

v_w is the wind velocity

Type	T_1 [°C]	T_2 [°C]	b	ΔT [°C]
Glass/cell/glass	25.0	8.2	−0.112	2
Glass/cell/tedlar	19.6	11.6	−0.223	3

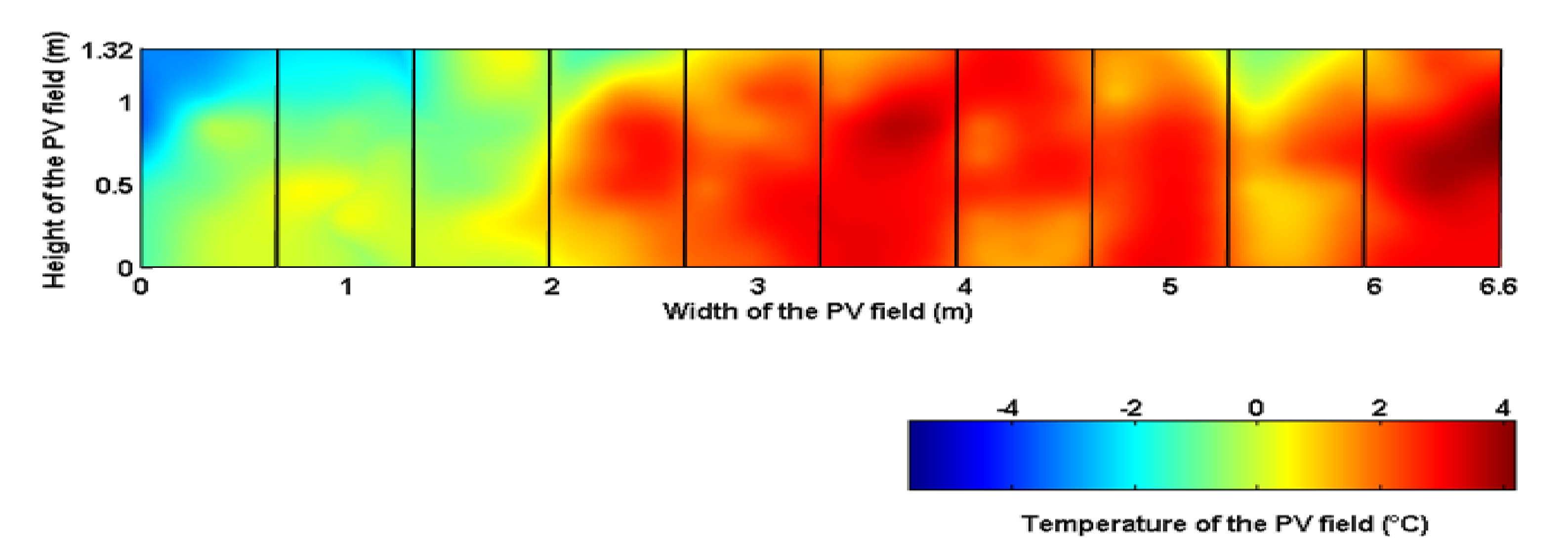
The cell temperature increse depends on the ambient temerature, the irradiance and the wind speed *w*

$$r_{thcab} = \frac{d_b}{\lambda_b} + \frac{1}{h_b} \qquad r_{thcaf} = \frac{d_f}{\lambda_f} + \frac{1}{h_f} \qquad h_k = A_k (w)^{3/4}$$

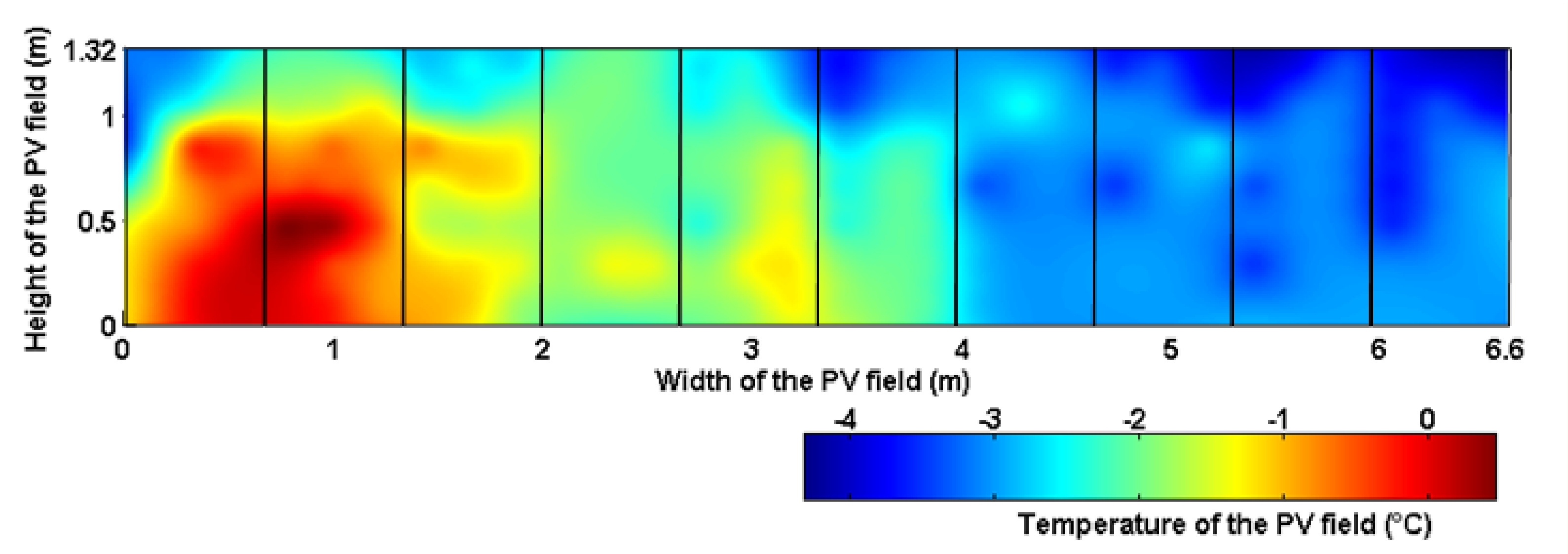


Temperature distribution over the PV field areas

45°

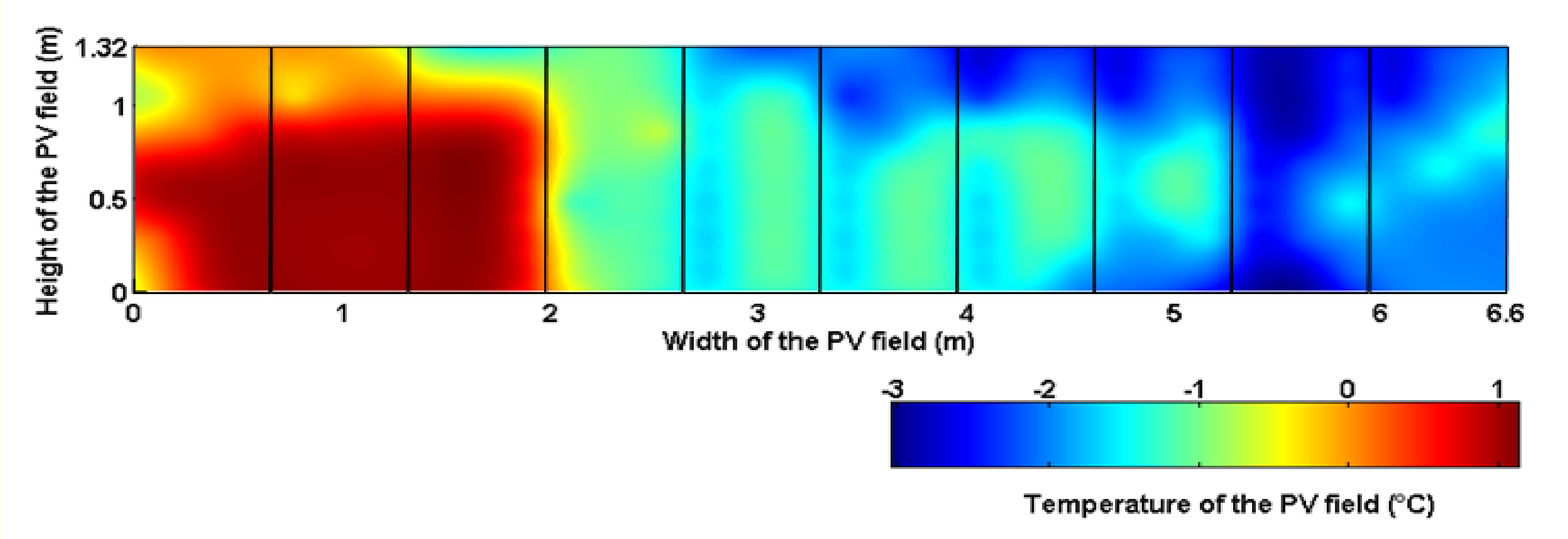


90°



Temperature distribution over the PV field areas

30° (roof)



The module temperature distribution is position sensitive

The cell operating temperature in the case of building integration

The building surface should be thermally isolated

Placing PV modules directly on the thermally isolated surface results in one-side cooling and consequently, in a higher operating temperature

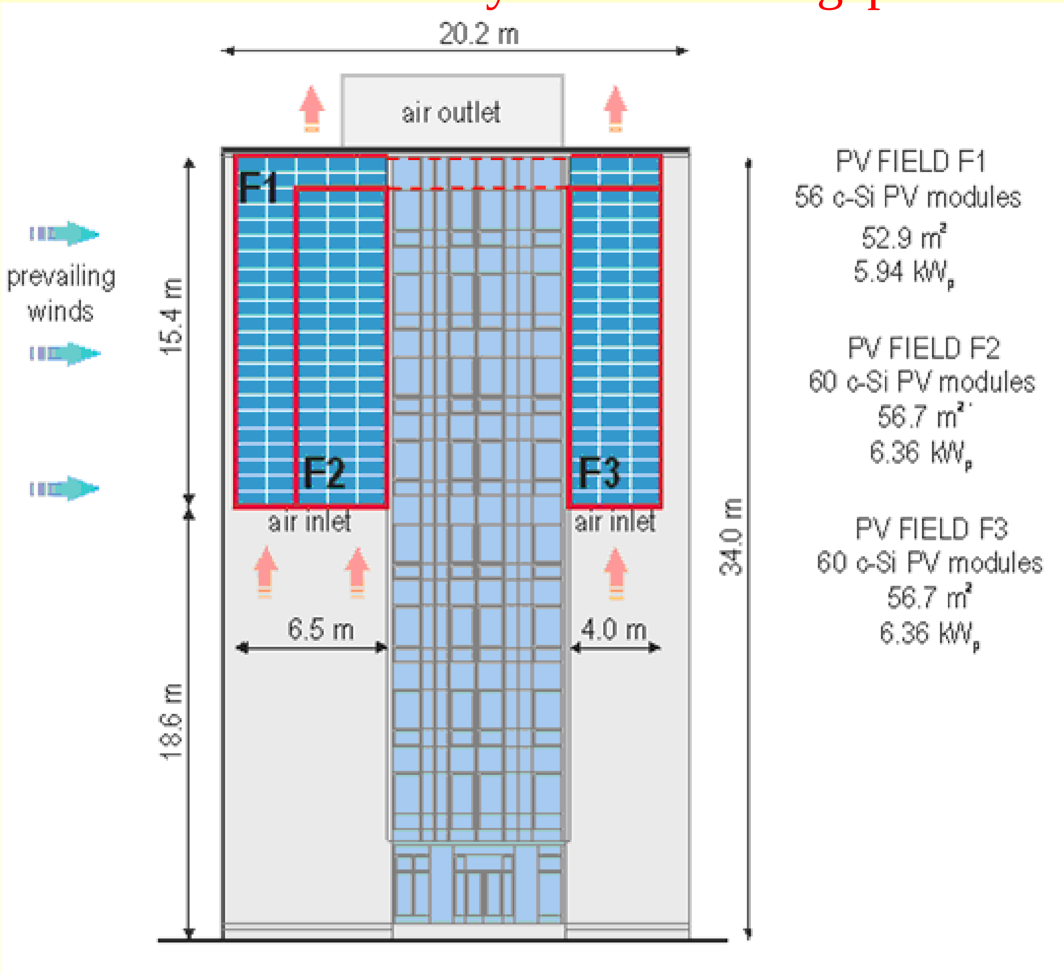
$$T_c = T_a + r_{thca} G_{ab} \qquad r_{\text{thca}} = \frac{r_{\text{thcaf}} r_{\text{thcab}}}{r_{\text{thcaf}} + r_{\text{thcab}}}$$

$$r_{thcaf} = \frac{d_f}{\lambda_f} + \frac{1}{h_f} \qquad r_{thcab} = \frac{d_b}{\lambda_b} + \frac{1}{h_b} \qquad r_{thcab} >> r_{thcaf} \implies r_{thca} \approx r_{thcaf}$$

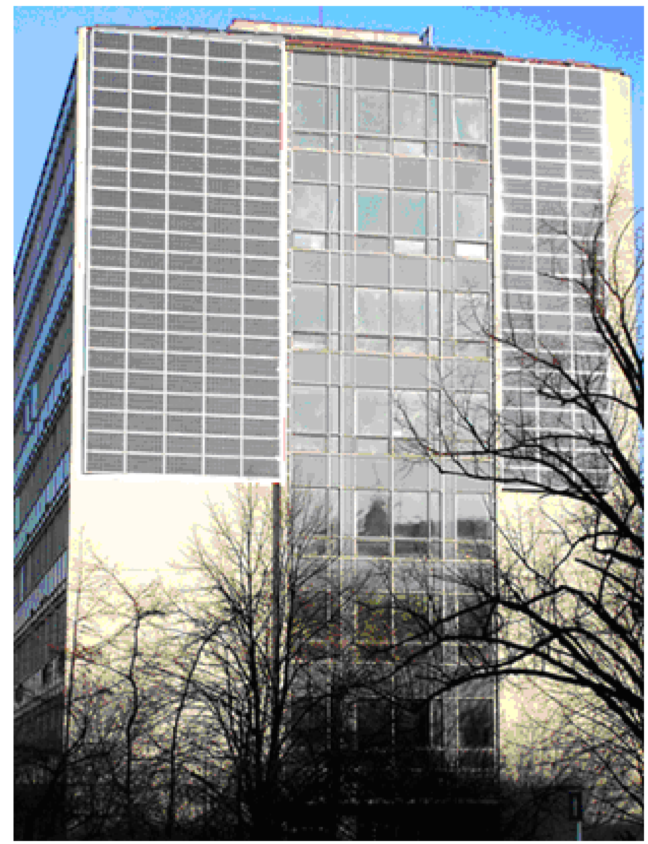
Cooling the back surface of PV modules is very important

Non-uniform temperature distribution on a back-ventilated PV façade

- south-west oriented, 3 independent PV fields (E1, E2, E3), 2 separated parts
- 176 c-Si PV modules Solartec SI72 110 W_p / 24 V, 18.66 kW_p in total, 166.3 m^2
- 100 mm wide naturally ventilated air gap between PV modules and insulated wall



- geometry of the PV facade -

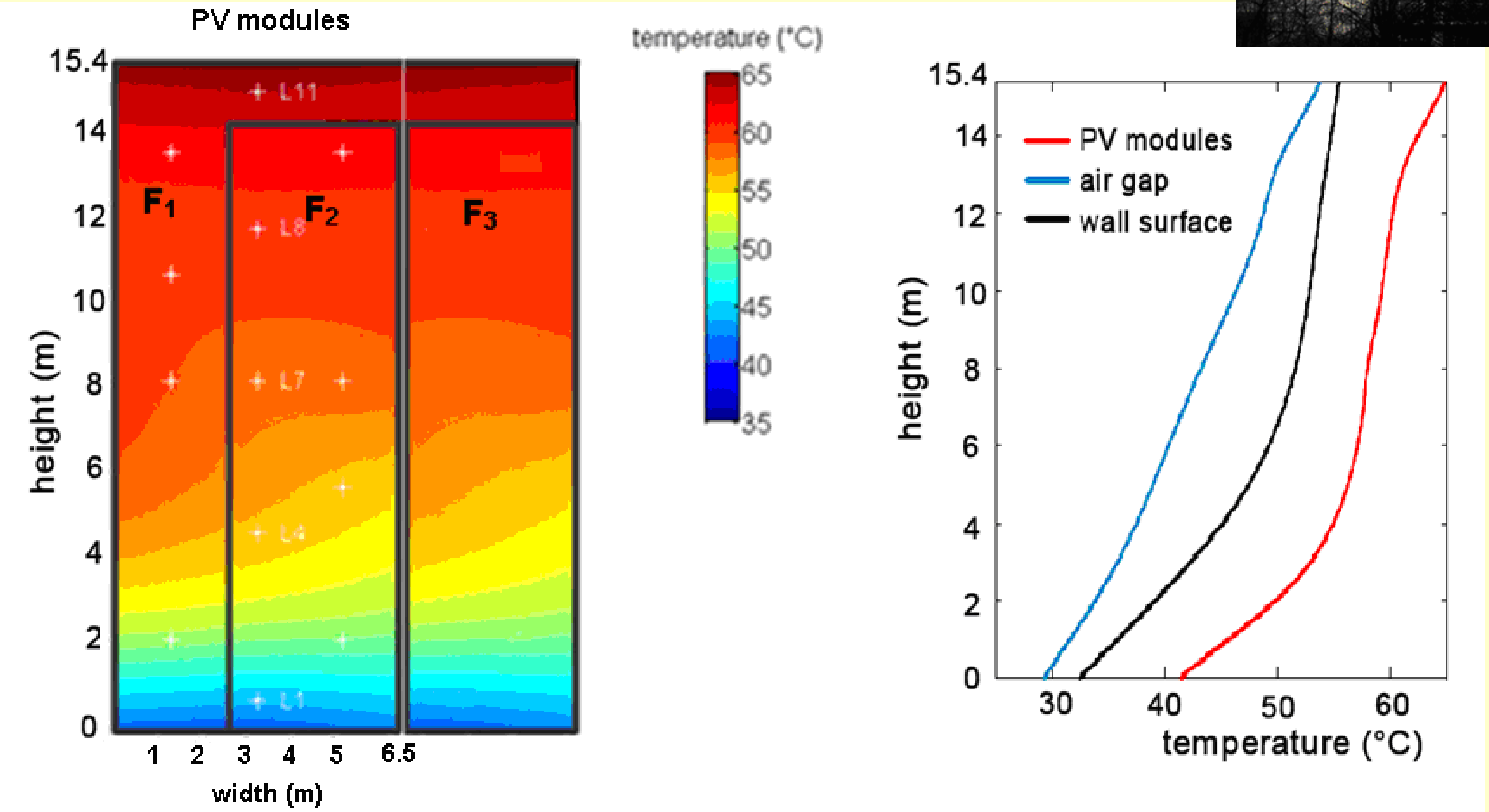


- photo of the PV facade -

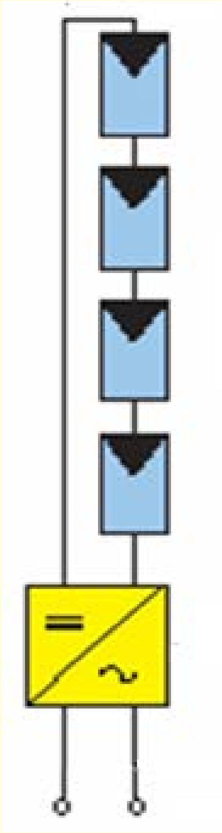
Temperature distribution

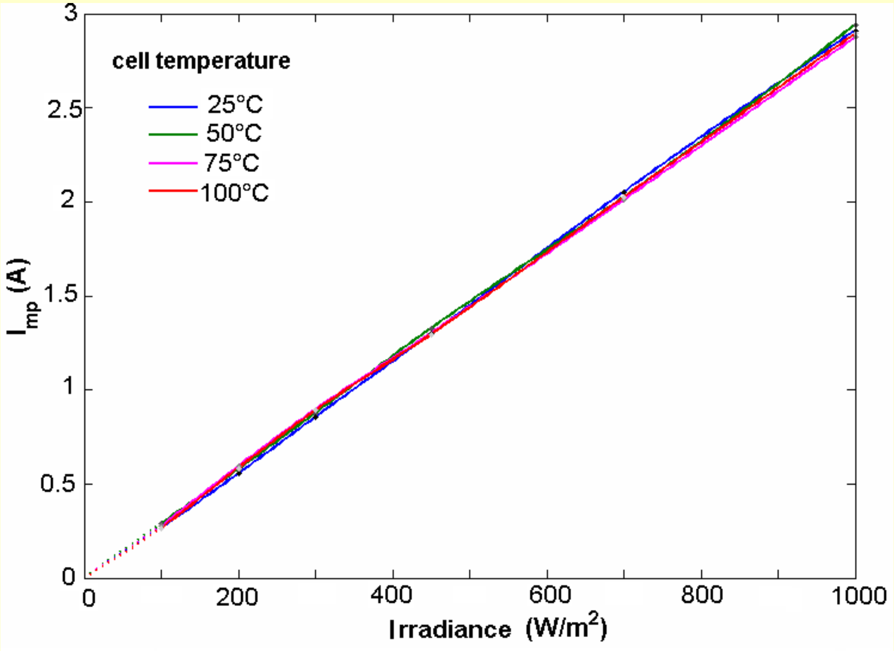
- daily peak temperatures at 16^{30} (30 min after irradiance peak)
- ambient conditions (G_{hor}=675 W/m^2, $G_{in\text{-}plane}$=644 W/m^2, amb. temp. 24.4 °C)

•the temperature distribution is highly non-uniform along the height



The string is operating at MPP $I = I_{mp}$



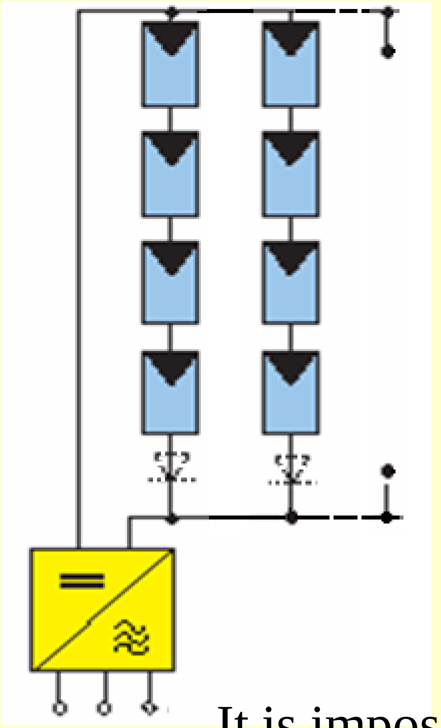


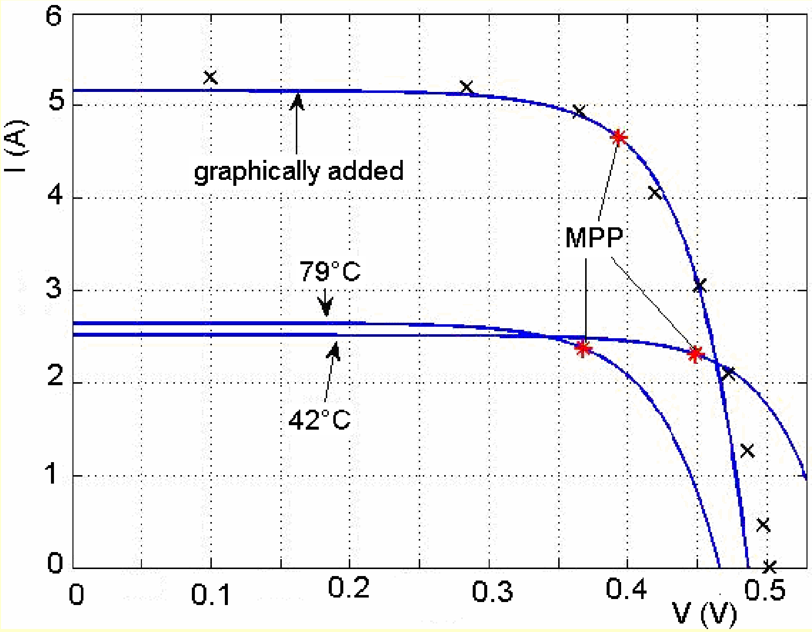
Experimentally found I_{mp} practically independent on temperature

$$P_{mp} = I_{mp} \sum_{i=1}^{n} V_{mp}(T_i) = n I_{mp} V_{mp}(T_{AV})$$

T_{AV} is average cell temperature in the string

Strings in parallel





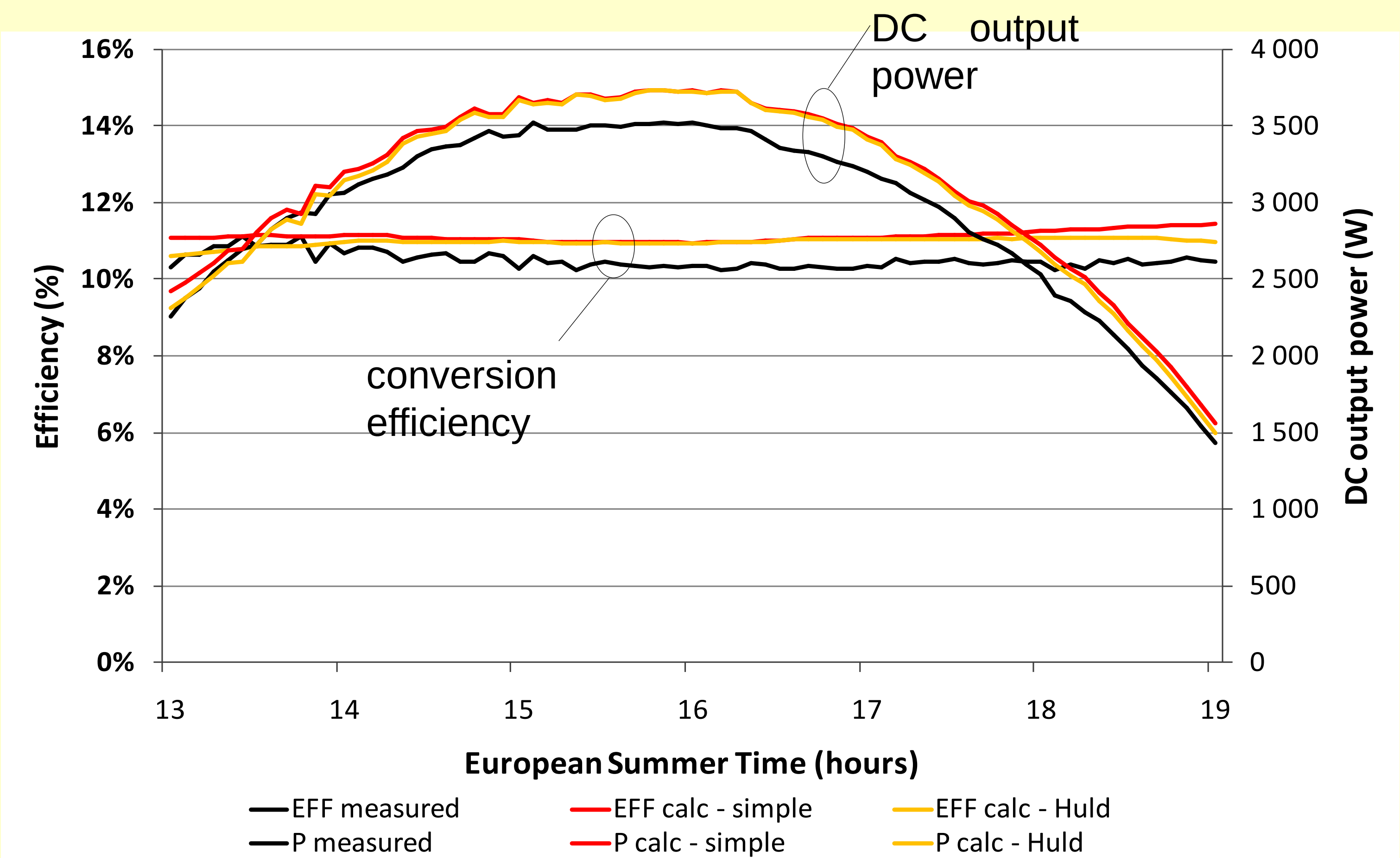
It is impossible to operate both in parallel connected cells (strings) of different temperatures in maximal power points (MPP) at the same time

The efficiency decrease due to in parallel connection of cells with different temperature was about 0.15% per °C in comparison with cells operated on the same (average) temperature

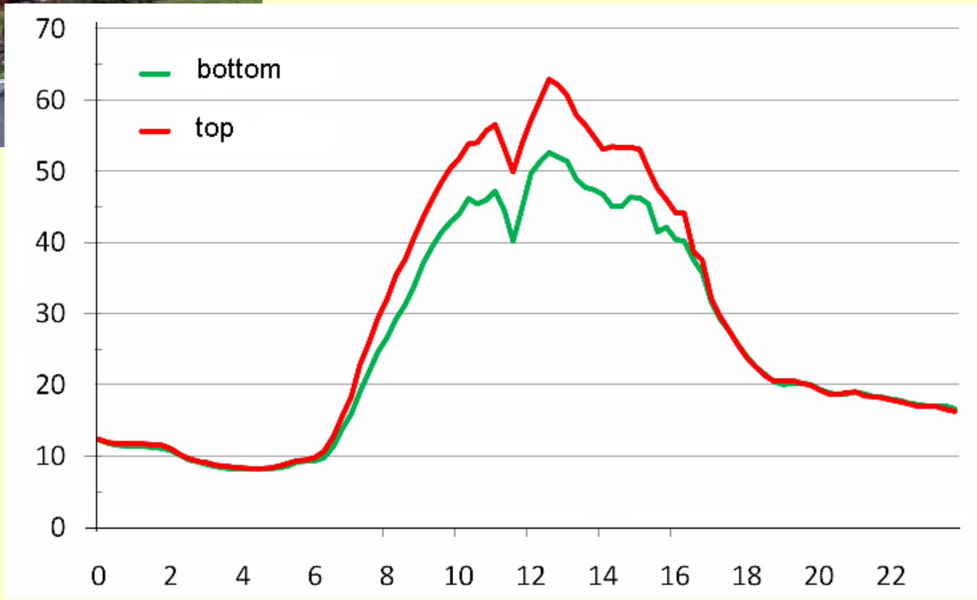
Measured vs. calculated profiles of conversion efficiency and DC output power for the façade PV field in the period of the highest temperature non-uniformity.

$$\eta_{conv} = \eta_{STC} \,.\, (1 + \gamma(T_{cell} - T_{cell,STC}))$$

$$\eta_{conv} = \eta_{STC} \,.\, (1 + \alpha I(T_{cell} - T_{cell,STC}).(1 + c_1 \,.\, ln(G/G_{STC}) + + c_2 \,.\, (ln(G/G_{STC}))^2 + \beta_V(T_{cell} - T_{cell,STC}))$$



100 mm wide naturally ventilated air gap between PV modules and the roof thermal isolation



Conclusions

- Facade PV system applications can produce about 66% of electrical energy produced by the roof (45° tilted) one
- Efficiency of PV systems is strongly influenced by temperature
- PV field constructions should allow an effective cooling of PV modules
- In parallel should be connected the module strings with the same average temperature