PV – PHOTOVOLTAICS

Part 4 : System Design & Engineering

Prof. M.Tognolini, HEIG-VD

Autheur: Prof. L. Bossoney, HEIG-VD

Table of contents

Table of contents (continued)

4.1 Collected Solar Energy

4.1.1 Introduction

- Solar Energy: is the energy source for life development on earth. Its enormous energy capacity represents more than 10'000 times the total energy consumed on earth.

- With a life time expectation of several billions of years it's the most reliable and long-term energy source known.
- Energy budget:
  - *Surface* required (*in Europe*) to cover the *world-wide electricity consumption* in 2012
    - 18'900 TWh
  - Surface 131'250 km^2
  - Efficiency 12 % and mean solar radiation of 1200 kWh/m^2/ year

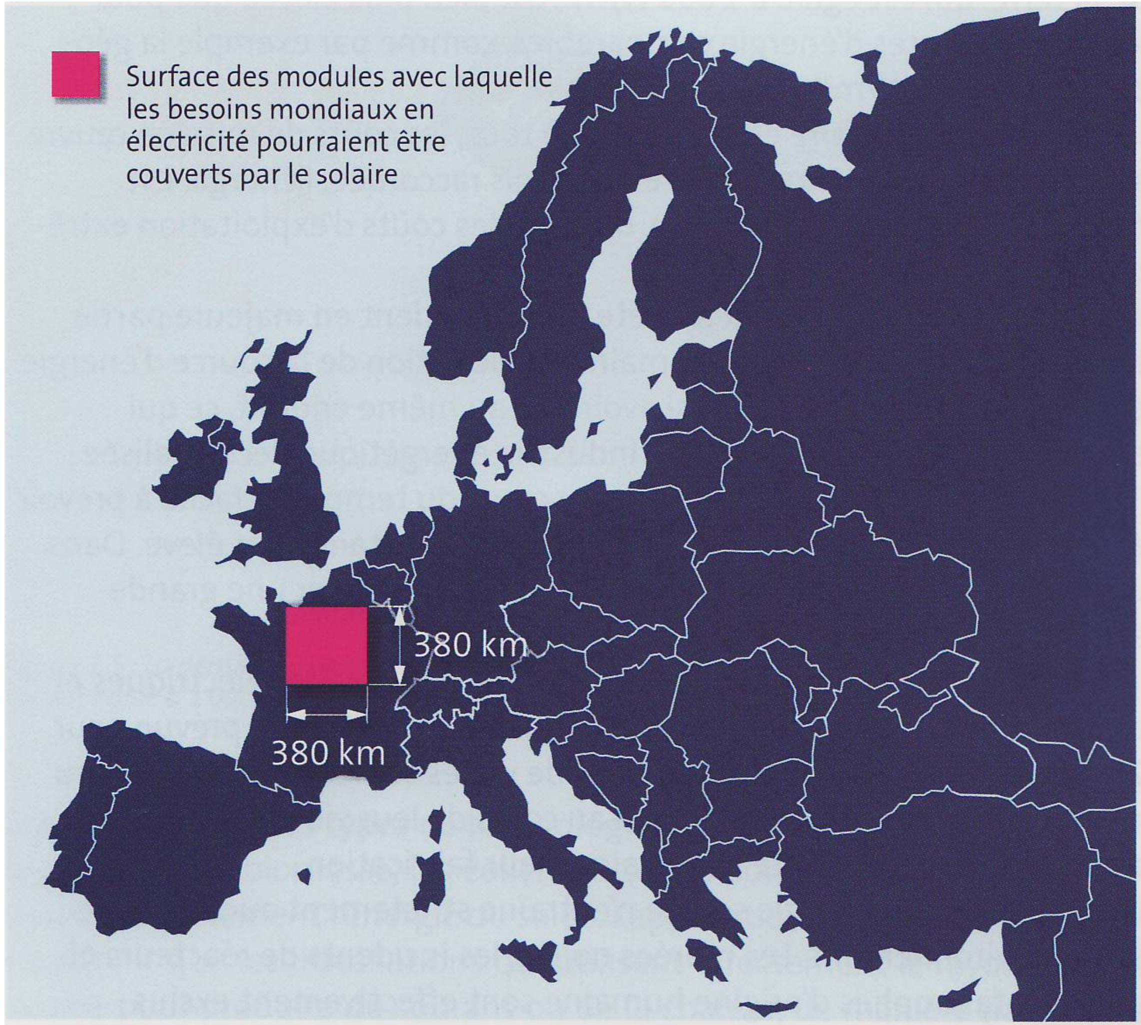
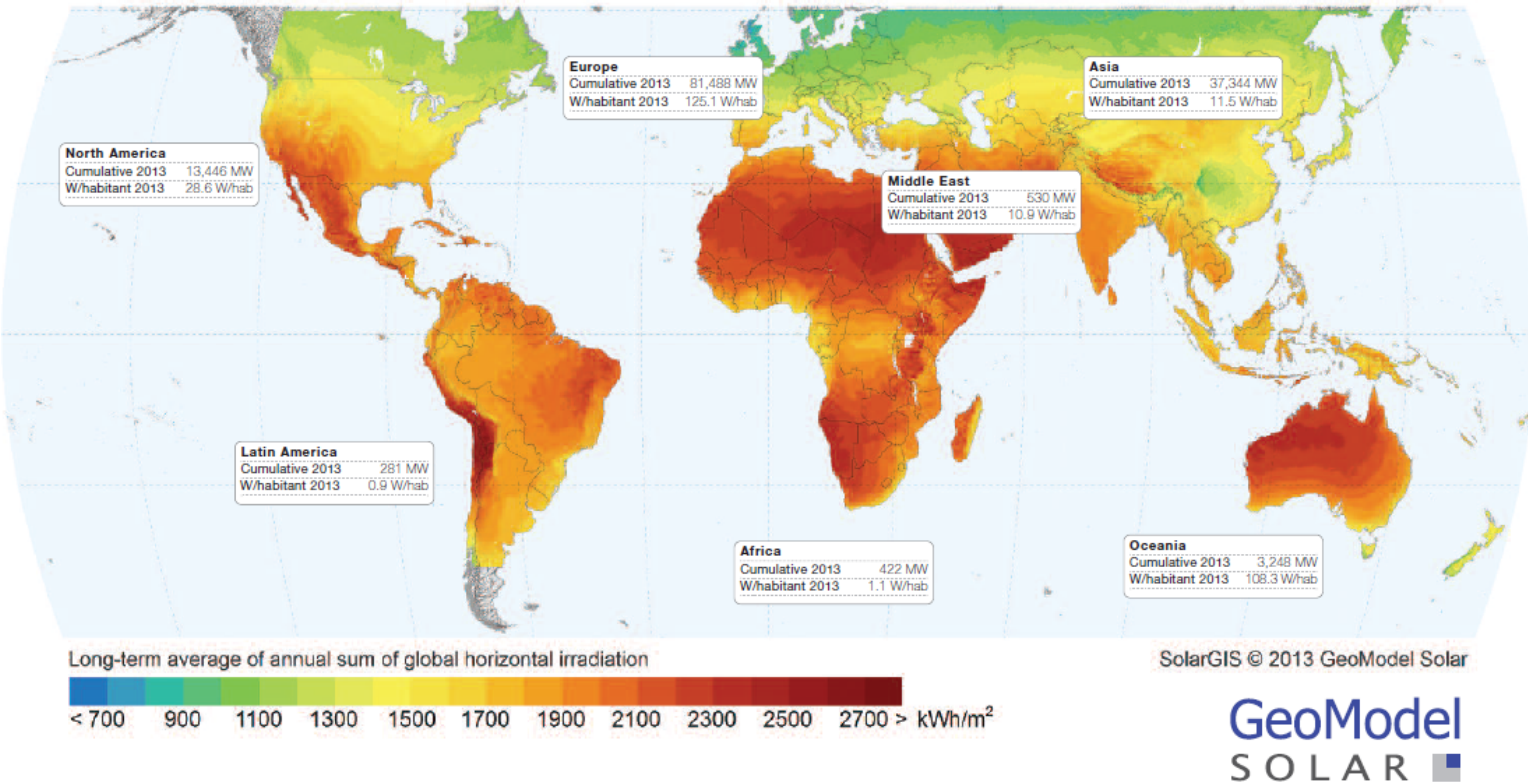


Fig 4.1: «PV pour tous»; collection. ObservER

Source: inforse.com

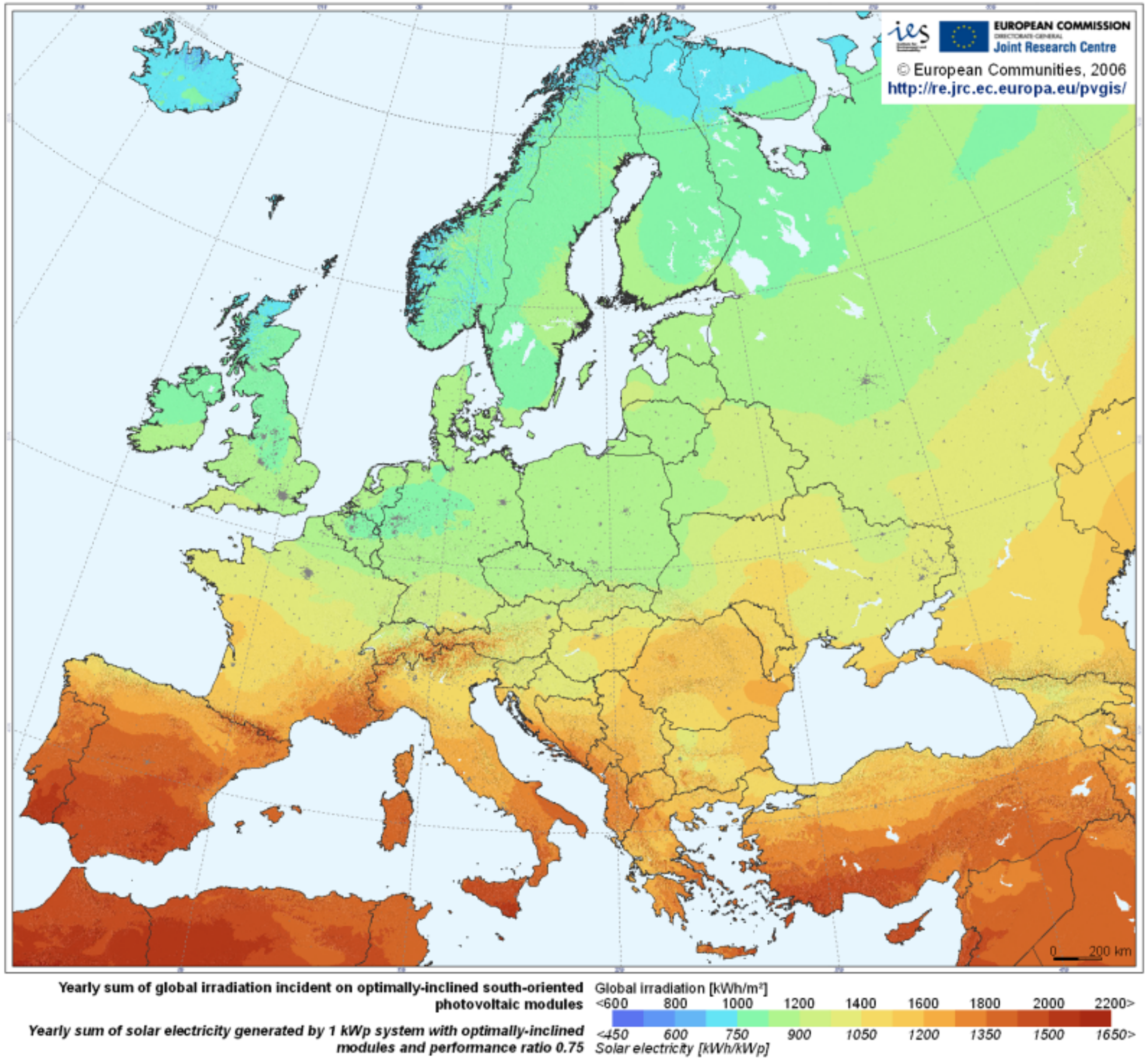
- **Worldwide yearly collected solar energy [kWh/m²/year]**:
  - **Useful for the design of PV panel size and resulting system power & energy estimation.**
  - **Cost per kWh will be different, depending on the geographic site of the PV power plant. The payback scenario may also be different.**



European yearly collected solar energy [kWh/m²/year]:

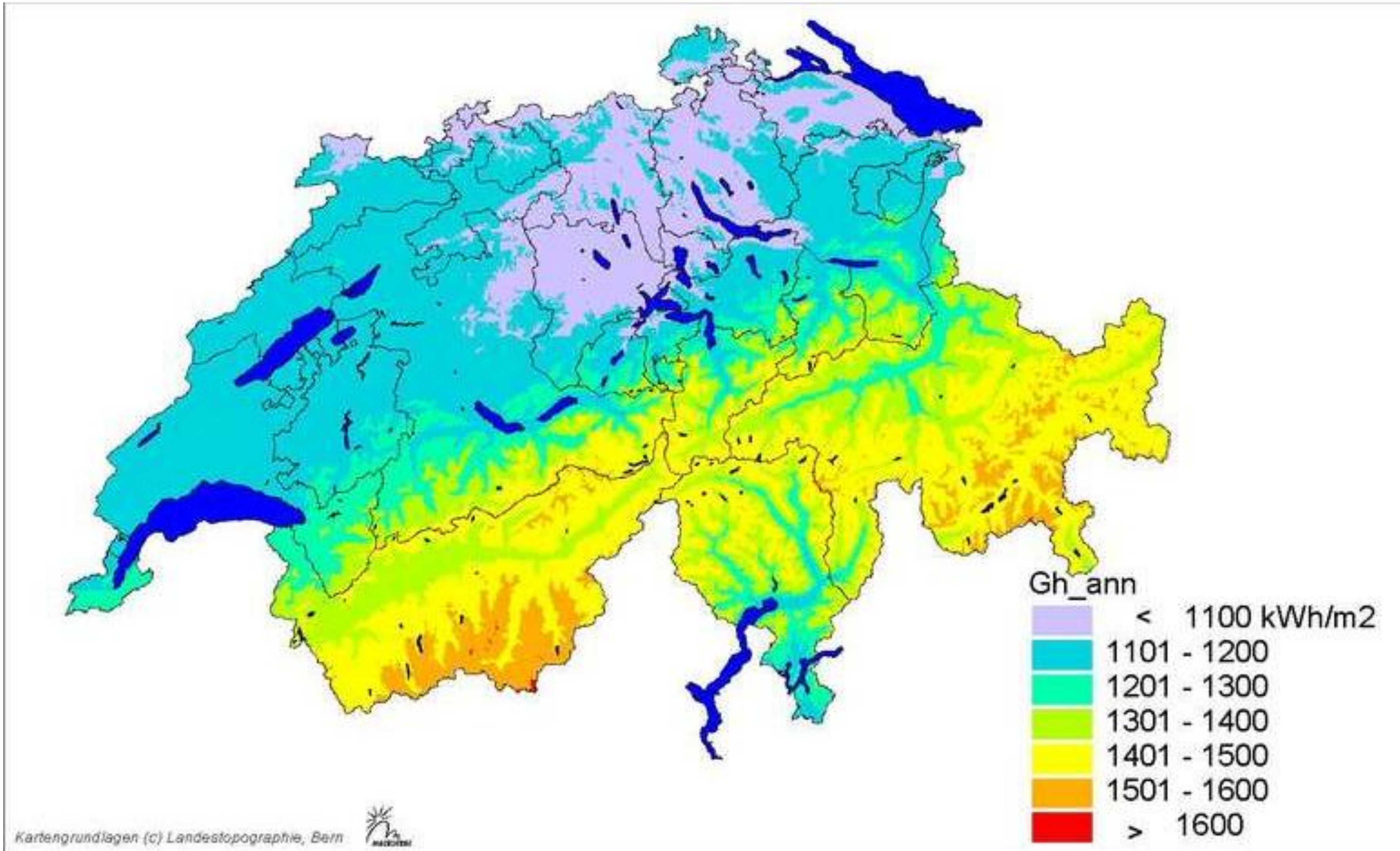
- **Peak values lower than max. world-wide values.**
- **North – South difference appears with some regional climatic differences.**

Photovoltaic Solar Electricity Potential in European Countries

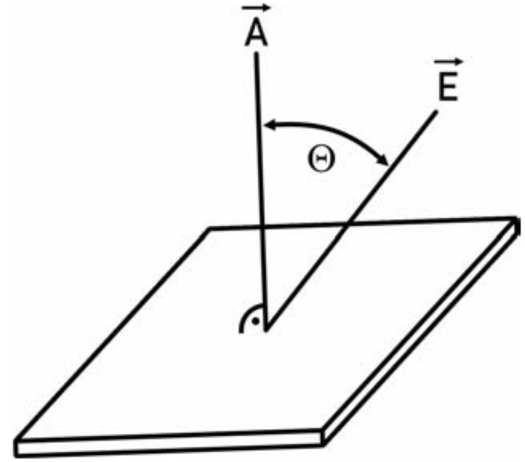


Source: EU, JRC (Joint Research Commission

In Switzerland the <u>yearly collected solar energy</u> is also depending on local geographic topology.



4.1.2 Direct radiation parameters



The (solar) flux Φ through a surface, given by its orthogonal surface vector $\bar{A}$, generated by an incident (solar radiation) vector $\bar{E}$ [W/m²] is given by the scalar vector product:

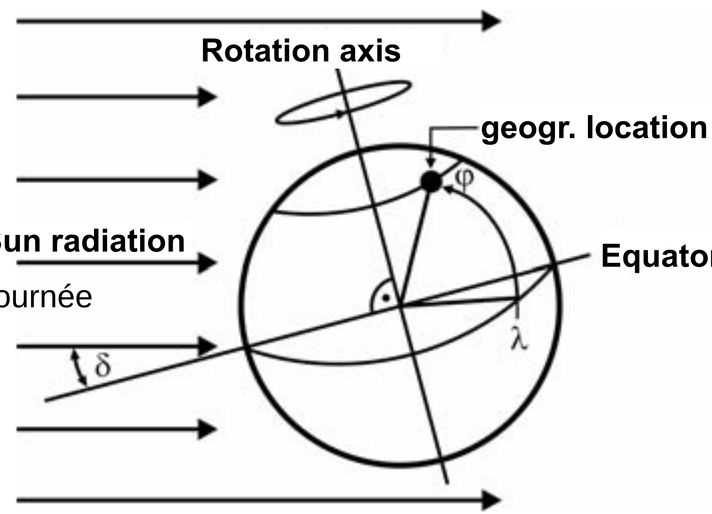
$$\Phi = E \cdot A \cdot \cos\Theta$$

On earth, for a given geographic location defined by:

- **the geographic latitude : φ (+N, -S)**
- **The geographic longitude : λ (+E, -W)**

The angle between both vectors, called solar zenith angle θ_Z will influence the solar incident factor $\cos\theta_Z$ following:

$$\cos\Theta_Z = \sin\delta \cdot \sin\varphi + \cos\delta \cdot \cos\varphi \cdot \cos\omega \qquad \textbf{(Eq. 4.1)}$$



Where :

- **ω is the sun azimuth angle, varying between 0 (noon) and $\pm\pi$ (midnight).** w : angle horaire du soleil durant la journée
- **δ is the declination angle, resulting from the inclination of the earth rotation axis. This declination angle is varying ± 23.45° between winter and summer time.**

The declination angle δ varies in function of the year day number N_d:

$$\delta = 23,45° \cdot \sin(360° \frac{284 + N_d}{365}) \quad \textbf{(Eq. 4.2)}$$

As a result of this, the <u>solar incident factor</u> $\cos\theta_Z$, can be <u>computed for a specific geographic location from sunrise to sunset for a given year date</u>. Fig. 4.11 shows the evolution of the solar incident factor , for the city of Lausanne (Switzerland) for different year dates. The evolution is proportional to the evolution of the (theoretic) direct sun radiation flux. It can be easily seen that between winter and summer, the max. sun radiation power varies more than a factor of two.

Geographic location of Lausanne:

- **geographic latitude :** $46°31.19' \text{ N}$
- **geographic longitude :** $6°38.01'$ **E**

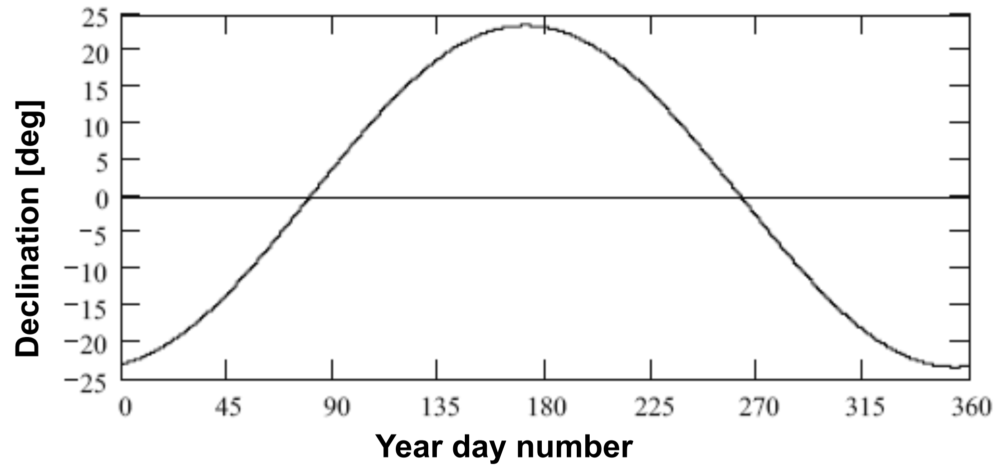


Fig. 4.10: yearly variation of the declination angle

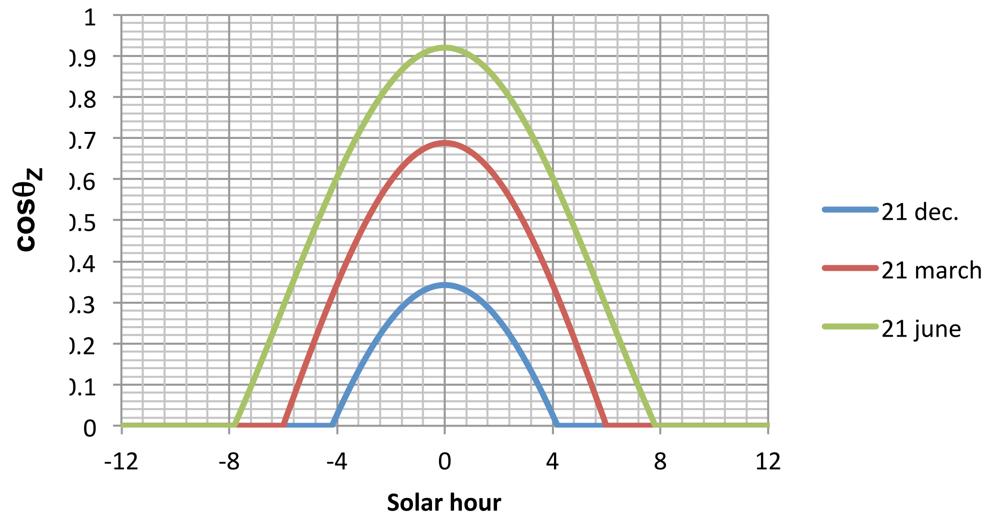


Fig. 4.11: **$\cos\theta_Z$** variation for the city of Lausanne

The solar incident angle can be significantly increased if the PV panel is tilted by a inclination angle s. Fig 4.12 shows the inclination angle (s) and azimuth orientation angle (a) of a tilted PV panel.

If the solar panel is tilted towards the equator (a=180°), the solar incident factor $\cos\theta_Z$, becomes then:

$$\cos\Theta_{\ddot{A}quator} = \sin\delta\cdot\sin(|\varphi|-s)+\cos\delta\cdot\cos(|\varphi|-s)\cdot\cos\omega \quad \textbf{(Eq. 4.3)}$$

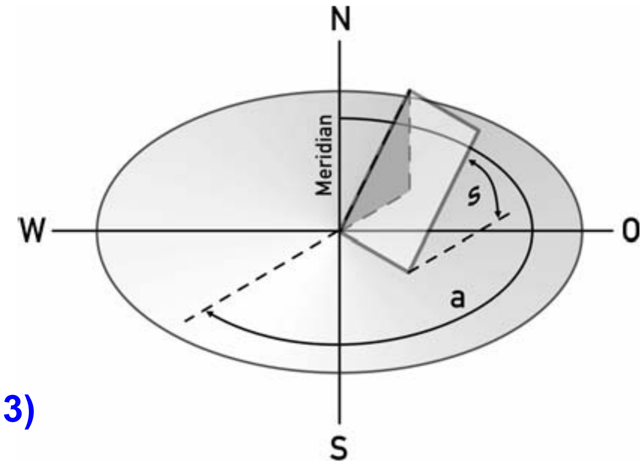


Fig. 4.12: inclination and azimuth orientation

As it can be seen on Fig. 4.13, the solar incident factor can be considerably increased compared to an "flat" solar panel and so will also be the increase of the solar incident radiation power.

The azimuth orientation factor is used to optimise the incident power (and energy !) in case of nearby buildings or other shadow generating objects.

The optimal inclination (s) and azimuth (a) angles to maximize the direct irradiation would be such as to generate a solar zenith angle θ_Z=0° (s=latitude angle φ , a=sunrise angle ω).

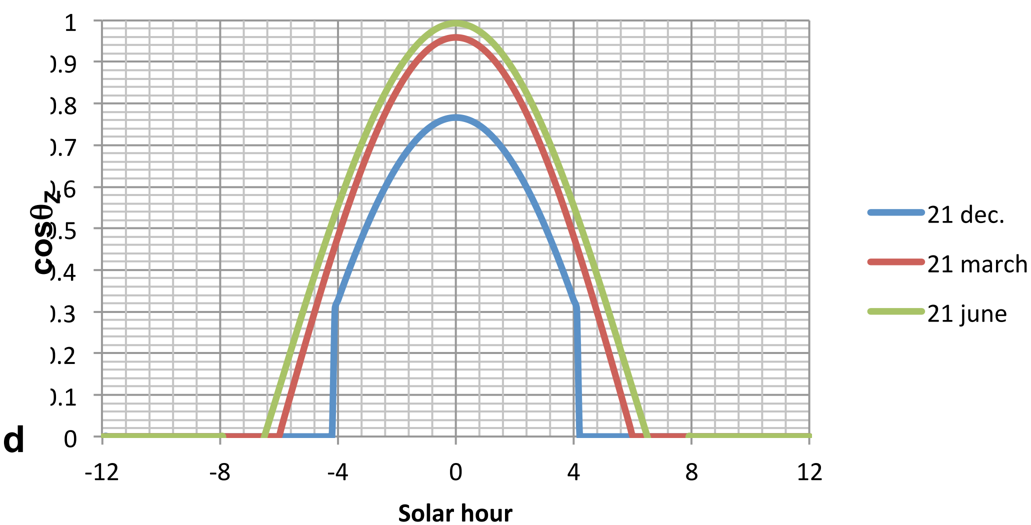


Fig. 4.13: solar incident factor with s=30° (Lausanne)

For a horizontal PV panel, the sunrise angle ω_s is given by :

angle lever/couchée du soleil

on pose cos(theta z)=0 ->

$$\omega_S = -\arccos(-\tan\delta \cdot \tan\varphi) \qquad \textbf{(Eq. 4.4)}$$

This corresponds obviously to a solar zenith angle of 90° (or cosθ_Z = 0). For a titled panel, having an inclination angle of s, oriented towards the equator (azimuth angle a =180°), the sunrise angle becomes:

$$\omega_S(s) = \max\left[\omega_S, -\arccos(-\mathrm{sgn}(\varphi)\cdot\tan\delta\cdot\tan(|\varphi| - s))\right] \qquad \textbf{(Eq. 4.5)}$$

The <u>theoretic direct solar irradiance</u>, without any atmosphere effect or influence, (also called extraterrestrial irradiance $B_o(0)$) is given by:

$$B_0(0) = B_0 \cdot e_0 \cdot \cos\theta_Z \qquad \textbf{(Eq. 4.6)}$$

where :

- **B_o is the solar constant = 1367 W/m². This value corresponds to the mean solar radiance outside of the atmosphere at one astronomical distance unit.**
- **e_o is the eccentric correction factor, taking into account, that the distance to the sun is not constant, as the earth is rotating on a ecliptic orbit around the sun.**

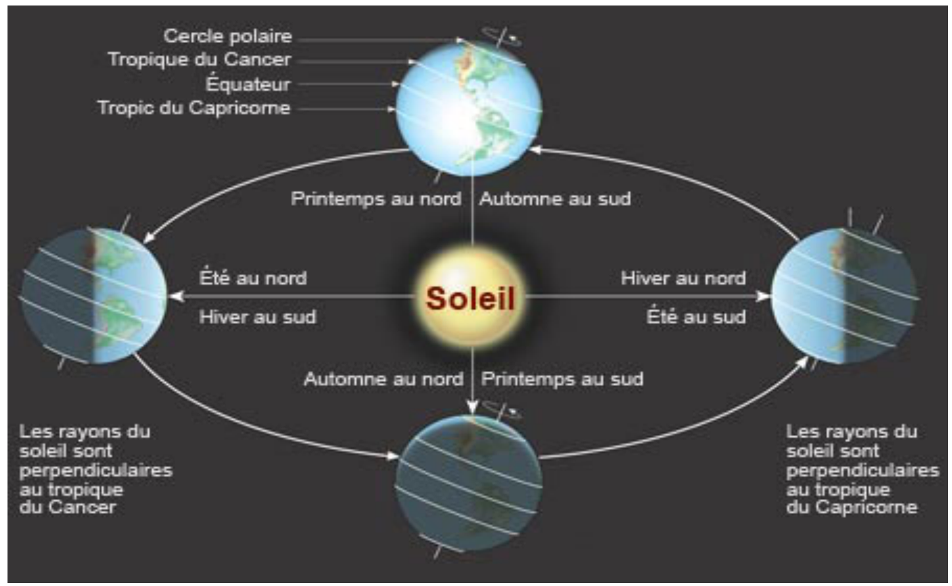


Fig. 4.14: ecliptic earth rotation plane

For engineering applications, the eccentric correction factor e_o can be approximated, using the year day number N_d with:

$$e_0 = 1 + 0.033 \cdot \cos\left(\frac{2\pi \cdot N_d}{365}\right) \quad \textbf{(Eq. 4.7)}$$

As the solar incidence factor $\cos\theta_Z$ is varying during the day, if we integrate the equation 4.6 for a day period, we obtain an estimation of the mean day extraterrestrial irradiation $B_{od}(0)$:

T : temps d'intégration en h, si on met s on obtient des Joules

$$B_{0d}(0) = \frac{T}{\pi} B_0 \cdot e_0 \left[-\omega_S \cdot \sin\delta \cdot \sin\varphi - \cos\delta \cdot \cos\varphi \cdot \sin\omega_S \right] \quad \textbf{(Eq. 4.8)}$$

ws en radian

Table 4.1 shows the computation result for the extraterrestrial irradiation data for Lausanne.

It can be shown, that the mean monthly extraterrestrial irradiation $B_{odm}(0)$ can be obtained for the day of the month, representing the mean declination angle of the month. This corresponds for each month for the date used in table 4.1.

As expected the maximum daily mean irradiation is obtained during the summer months and the lowest during winter.

Month	$G_{dm}(0)$ [kWh/m²]	day	N_d	δ [°]	e_o	ω_s [°]	$B_{odm}(0)$ [kWh/m²]
January	1.16	17	17	-20.92	1.0316	-66.2	3.085
February	1.82	14	45	-13.62	1.0236	-75.2	4.478
March	3.4	15	74	-2.82	1.0097	-87.0	6.611
April	4.2	15	105	9.41	0.9923	-100.1	9.000
May	5.5	15	135	18.79	0.9774	-111.0	10.742
June	5.84	10	161	23.01	0.9692	-116.6	11.481
July	5.6	18	199	21	0.9683	-113.9	11.077
August	5.14	18	230	12.78	0.9774	-103.8	9.543
September	3.9	18	261	1.01	0.9928	-91.1	7.284
October	2.19	19	292	-11.05	1.0102	-78.1	4.932
November	1.3	18	322	-19.82	1.0244	-67.7	3.271
December	0.99	13	347	-23.24	1.0314	-63.1	2.656

valeur mesurée : valeur moyenne du mois

valeur théorique

Table 4.1: Extraterrestrial mean radiation for Lausanne

le reste est absorbée par l'atmosphère, ...

4.1.3 Radiation components

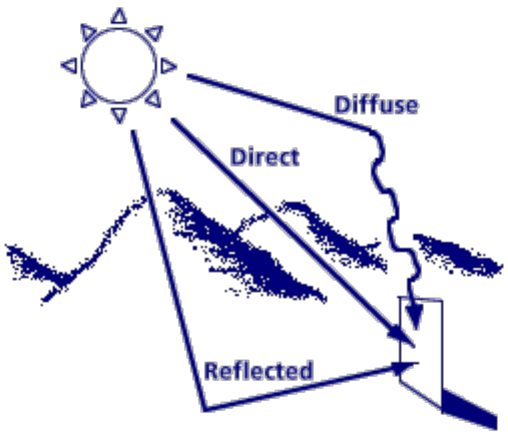


Fig. 4.15: Solar irradition types

The incident radiation collected on a solar panel may has different components (origins):

- **Direct radiation from sun to solar panel.**
- **Diffuse radiation : depending on different reflection and absorption effects in the air atmosphere.**
- **Reflected radiation (or albedo) from other objects & surfaces**

The mean radiation budget can be estimated from global energy budget calculations (see fig. 4.16). These estimations depend much on:

- **Local topology of considered area.**
- **Altitude : affecting the air absorption factor.**
- **Climatic influences (rain, fog, etc.)**
- **Reflection coefficient on surroundings**

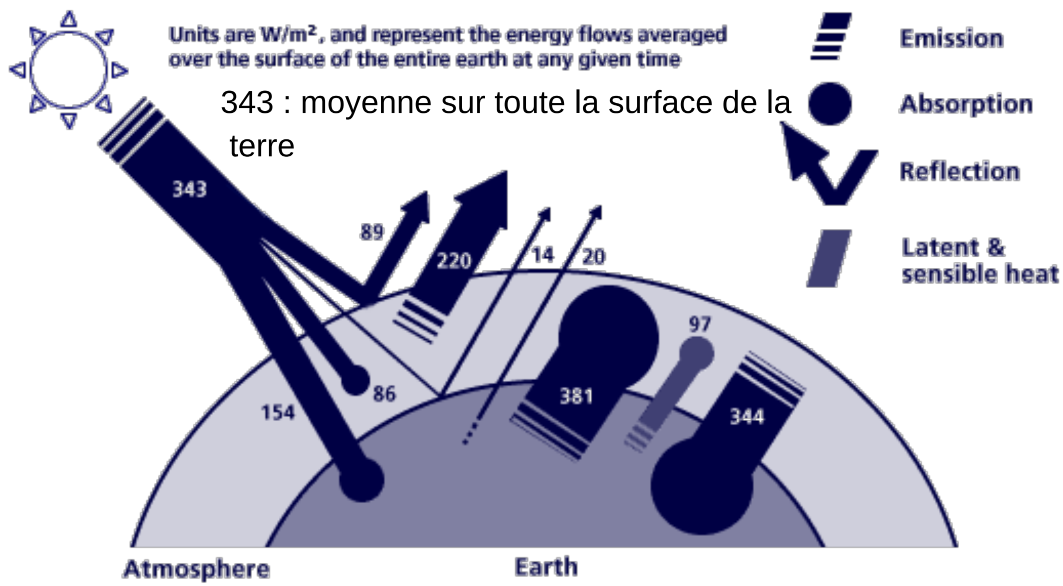


Fig. 4.16: Emission, absorption and reflection energy budgets

The albedo (on tilted solar panels only) depends on the reflection coefficient ρ of the surrounding surfaces. Table 4.2 shows the reflection coefficients of some surface areas.

An important concept characterising the effect of atmosphere on clear days is the air mass AM, defined as the relative length of the direct-beam path through the atmosphere compared with a vertical path directly on sea level. For an ideal homogenous atmosphere, simple geometrical considerations lead to:

$$AM = \frac{1}{\cos\theta_Z} \qquad \text{(Eq. 4.9)}$$

At the standard atmosphere, AM1, the normal irradiance on earth is reduced from B_0 to 1000 W/m^2, which is also the SRC value used (see §3.1.5.1).

For higher AM values, absorption and diffusion effects will be higher, whereas direct and reflected irradiation will lower down and vice versa.

Mean values for absorption, diffusion and reflection will much depend on climatic and weather conditions.

Environment	*Albedo p.u.]*
City, urban environment	0,14-0,22
Grass	0,15-0,26
Forest, trees	0,08-0,18
snow	0,8-0,9
Melted snow, ice	0,55-0,75
Dry asphalt	0,09-0,15
Desert sand	0,4
concrete	0,25-0,35
Red tiles	0,33
Aluminium	0,85
Galvanic iron (new)	0,35
Galvanic iron (aged)	0,08
lake	0,02 – 0,04
Sea (salted water)	0,05 – 0,15

Table 4.2: Reflection coefficients

Le meilleur rendement est obtenu en juin.
Les mois de juillet et août sont plus chauds à cause de phénomènes climatiques (par exemple convection) comme l'inertie de la météo.

4.1.4 Satistic irradiation data

To take into account the (almost) unpredictable variation of weather conditions, atmosphere and solar power changes, periodic radiation measurements can be used to constitute statistic mean irradiation databases, reflecting the local climatic and geographic conditions of the measured point.

Fig. 4.17 shows the mean daily irradiation data, over each month $G_{dm}(0)$, for a horizontal surface in Lausanne [7](for detailed values see Table 4.1).

The collected data allows to evaluate :

- **The mean daily irradiation over one year:**

énergie d'un jour moyennée sur l'année

$$\overline{G_{dy}}(0) = 3.43\ \mathrm{kWh}/m^2$$

- **The standard deviation over one year:**

ecart-type

$$\overline{\sigma_{dy}}(0) = 1.87\ \mathrm{kWh}/m^2$$

- **The mean yearly global radiation:**

$$G_y(0) = 1252\ \mathrm{kWh}/m^2$$

Assuming the statistic daily irradiation follows a Gaussian (normal) distribution, following confidence intervals can be evaluated:

- **68% confidence for $\overline{G_{dy}}(0) \pm \overline{\sigma_{dy}}(0)$**
- **90% confidence for $\overline{G_{dy}}(0) \pm 1.64 \times \overline{\sigma_{dy}}(0)$**

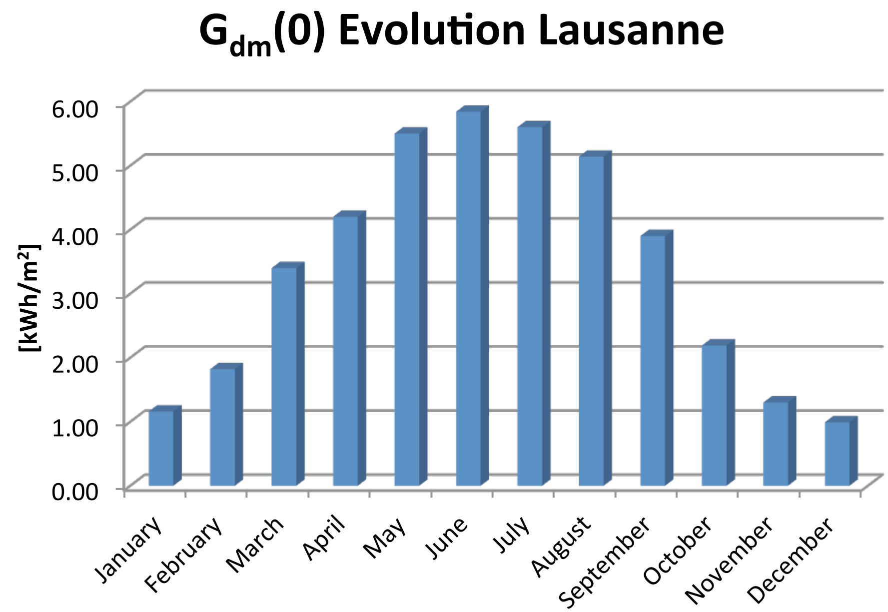
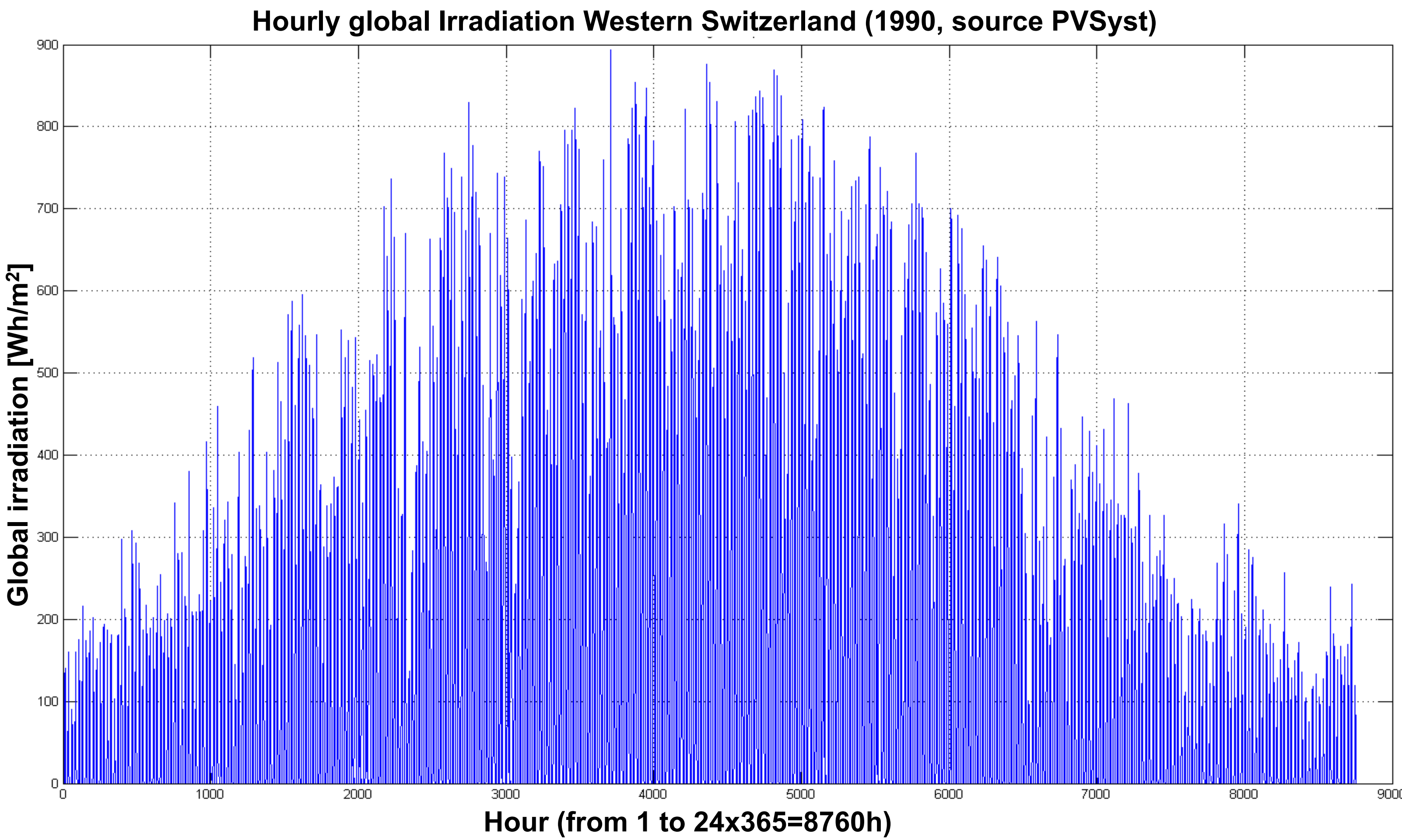


Fig. 4.17: $G_{dm}(0)$ evolution for Lausanne

$$\overline{G_{dy}}(0) = \frac{1}{n}\sum_{i=1}^{n}\left(G_{dm}\right)_i \qquad \overline{\sigma_{dy}}(0) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\overline{G_{dy}} - G_{dm\,i}\right)^2}$$

Other irradiation data may be collected on a hourly based database (see example below). Such databases, used for SW assisted design of PV systems, generate more precise (confident) data.



4.1.5 Collected Solar Energy on arbitrary surface

In order to practically estimate the direct (or beam) $B_{dm}(s)$, the diffused $D_{dm}(s)$ and reflected $R_{dm}(s)$ irradiations, a simple calculation method, based on measurement statistics, geometric (inclination angle s) and geographic data has been developed (details see [7]).

A clearness index K_{Tm}, indicating the atmospheric transparency, can be evaluated by comparing the mean solar irradiation measured on earth $G_{dm}(0)$ and the corresponding extraterrestrial irradiation $B_{0dm}(0)$:

clarté de l'atmosphère : définit la part absorbé par l'atmosphère

$$K_{\mathrm{Tm}} = \frac{G_{dm}(0)}{B_{0dm}(0)} \qquad \textbf{(Eq. 4.10)}$$

In similar way a diffuse fraction coeficient F_{Dm} can be defined with $F_{Dm} = D_{dm}(0) / G_{dm}(0)$. As seen in §4.1.3, the clearer the atmosphere, the higher the radiation and the lower the diffuse content. Hence following empiric relation between K_{Tm} and F_{Dm} has been established [7]:

$$F_{\mathrm{Dm}} = 1 - 1.13 \cdot K_{\mathrm{Tm}} \qquad \textbf{(Eq. 4.11)}$$

Regarding the direct irradiation on a tilted surface, with a inclination angle of s and oriented towards the equator, follows the relations:

$$\left.\begin{aligned}
&\text{partie diffuse} && D_{\mathrm{dm}}(0) = F_{\mathrm{Dm}} \cdot G_{\mathrm{dm}}(0) \\
&\text{rayonnement direct} && B_{\mathrm{dm}}(0) = G_{\mathrm{Dm}}(0) - D_{\mathrm{dm}}(0) \\
&\text{rayonnement selon inclinaison du panneau} && B_{\mathrm{dm}}(s) = B_{\mathrm{dm}}(0) \cdot RB
\end{aligned}\right\} \textbf{(Eq. 4.12)}$$

Where RB represents the ratio between the direct irradiation on a inclined and a horizontal surface. This ratio can be obtained by comparing the integrals of equations 4.1 and 4.3. Hence:

Beam Ratio RB : $$RB = \frac{\omega_S(s)\cdot \mathrm{sgn}(\varphi)\cdot \sin\delta \cdot \sin(|\varphi| - s) + \cos\delta \cdot \cos(|\varphi| - s)\cdot \sin\omega_S(s)}{\omega_S \cdot \sin\delta \cdot \sin\varphi + \cos\delta\cdot\cos\varphi\cdot\sin\omega_S}$$ **(Eq. 4.13)**

The diffused $D_{dm}(s)$ and reflected $R_{dm}(s)$ irradiation levels can be obtained, using the assumption of isotropic atmosphere conditions and the use of the reflection ratio ρ:

$$D_{dm}(s) = D_{dm}(0)\cdot \frac{1+\cos(s)}{2}$$ **(Eq. 4.14)**

$$R_{dm}(s) = \rho \cdot G_{dm}(0)\cdot \frac{1-\cos(s)}{2}$$ **(Eq. 4.15)**

Finally, the global mean daily irradiation obtained for a tilted plain (inclination angle s) is simply obtained by :

$$G_{dm}(s) = B_{dm}(s) + D_{dm}(s) + R_{dm}(s)$$ **(Eq. 4.16)**

Using more empiric estimations and measuring methods (see [7]), an optimal inclination angle can be estimated, using:

$$s_{opt} \cong 3.7 + 0.69\cdot|\varphi|$$ **(Eq. 4.17)**

In general using higher inclination angles will increase the winter-time period irradiation meanwhile the summer-time period irradiation may be decreased by lowering the sunrise and sunset azimuth angles (see also fig. 4.11 and 4.13). Due to the fact that the atmospheric conditions during winter-time are less favourable than during summer-time, a purely direct radiation based approach should be challenged and reconsidered carefully.

Comparaison tilted and horizontal plane yearly collected solar energy [kWh/m²/year]:

- **Increase of 10% to 20% compared to horizontal plane PV panel.**
- **Increase higher on better exposed areas (high altitude, south orientation, lower climatic influences) than on areas with less favourable climatic conditions.**

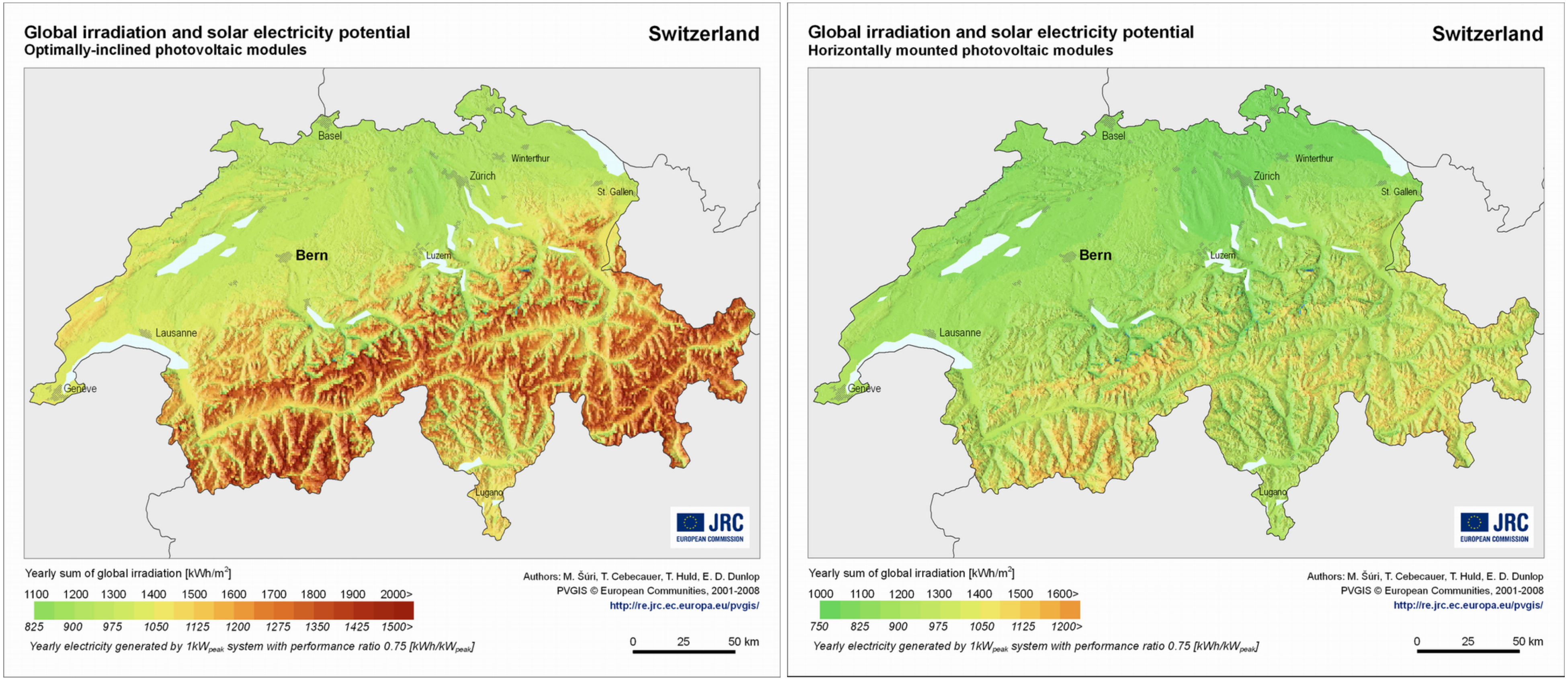


Fig. 4.20: collected solar energy with optimal angle (left) and horizontal PV panel (right). Source: JRC 2012

Comparaison inclination and aziuth angle on yearly collected solar energy [kWh/m²/year]:

- **PVSYST based study for Geneva (sources Meteonorm , Nowak Energie &Technologie SA).**
- **Inside a certain safe area (inclination 20°< s < 40° and azimuth ±30°), the yearly collected energy has a minor variation (less than 5%).**

- **Useful for «choosing» of optimal orientation for avoiding shadow-generating objects**

Le plus important est de rester dans la zone centrale. on peut meme avoir une orientation de +/- 30°.
Si on a un panneau orienté à 20°, ce n'est pas la peine de monter à 30° car l'énergie reçue est la même

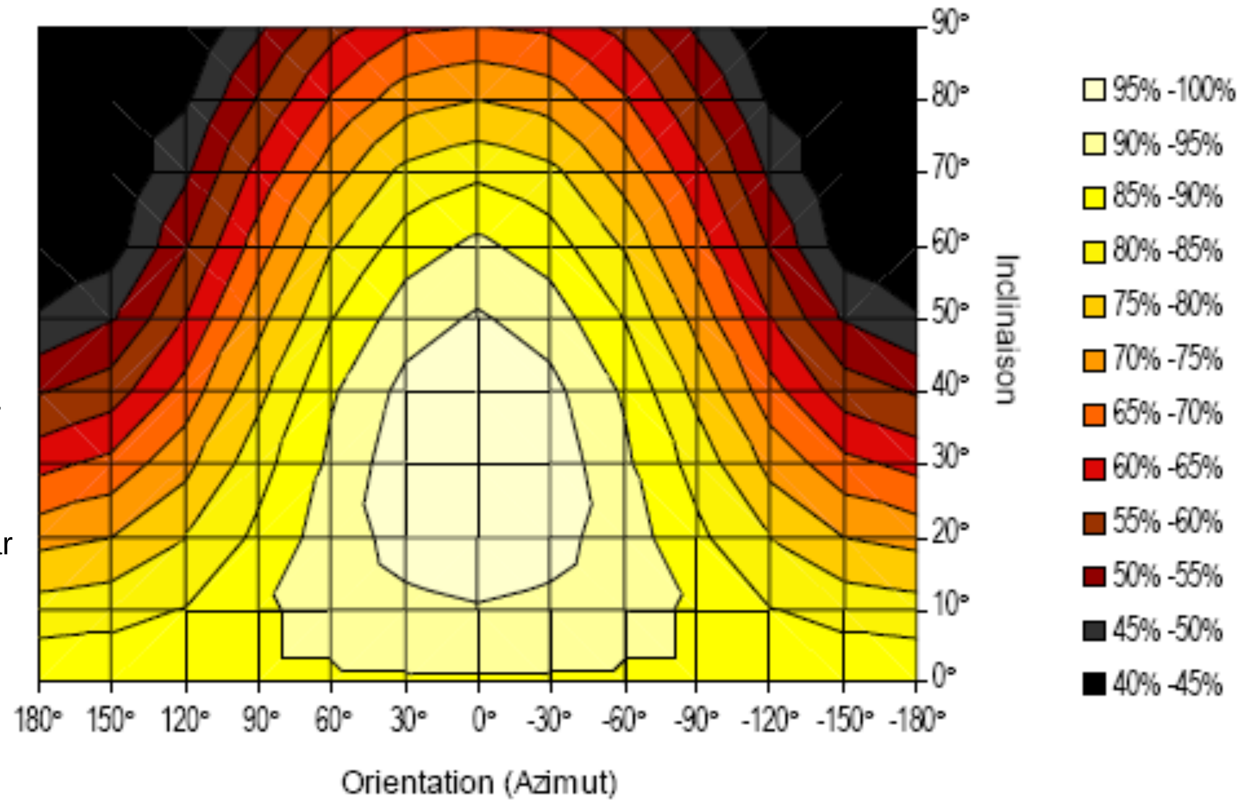


Fig. 4.21: collected solar energy as a function of inclination and azimuth angle

4.1.6 Shadows and other effects

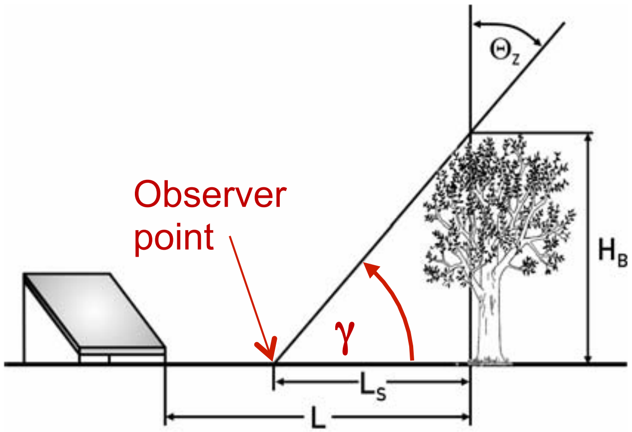


Fig. 4.22: Elevation angle of shadowing object

Objects supposed to generate shadows on PV panels are to be identified with their respective azimuth and elevation angle profile.

Fig 4.22 shows the elevation angle of a shadow generating object defined from an observing point.

The identified azimuth and elevation angle profile can be reported on the sun elevation angle profile of the location (Fig. 4.23) to identify any effect on the “effective” sunrise resp. sunset angles.

The loss of energy may be bypassed or lowered by choosing a different azimuth orientation of the PV panel.

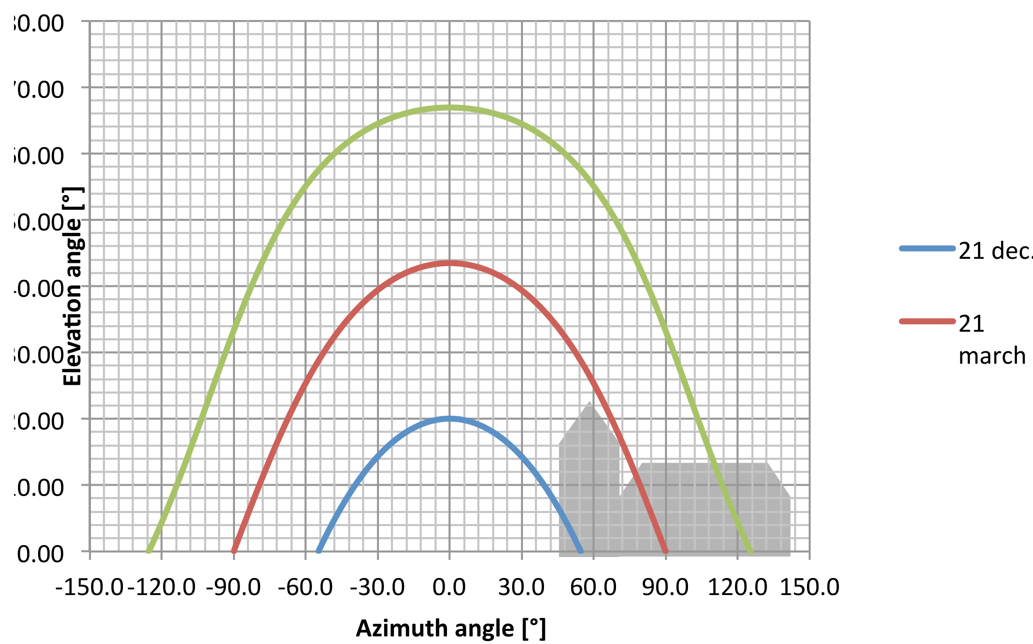


Fig. 4.23: Elevation & azimuth angle of sun & shadow object

Apart from the mentioned shadow effects, dirt deposit, (sand, dust, guano, etc.) can also considerably affect the energy yield of a PV panel. On regions with "sufficient" rain showers and with tilted solar panel, there is obviously no much effect. On the other hand, for locations having an important solar energy potential, in other terms locations with:

- **High direct solar irradiation (therefore close to the equator) and consequently with lower inclination angles of the PV panel.**
- **Poor rainfall periods.**
- **Exposed to sand "storms" or other dirt deposit.**

Are highly concerned with such kind of energy efficiency lost.

Fig. 4.24 shows an experimental measurement showing the drastic PV energy loss, up to 80%, due to dirt impact and linked to the cleaning frequency of the PV panels. In addition to mentioned dirt deposit, the cleaning may be also a matter of costs, in countries with poor water resources.

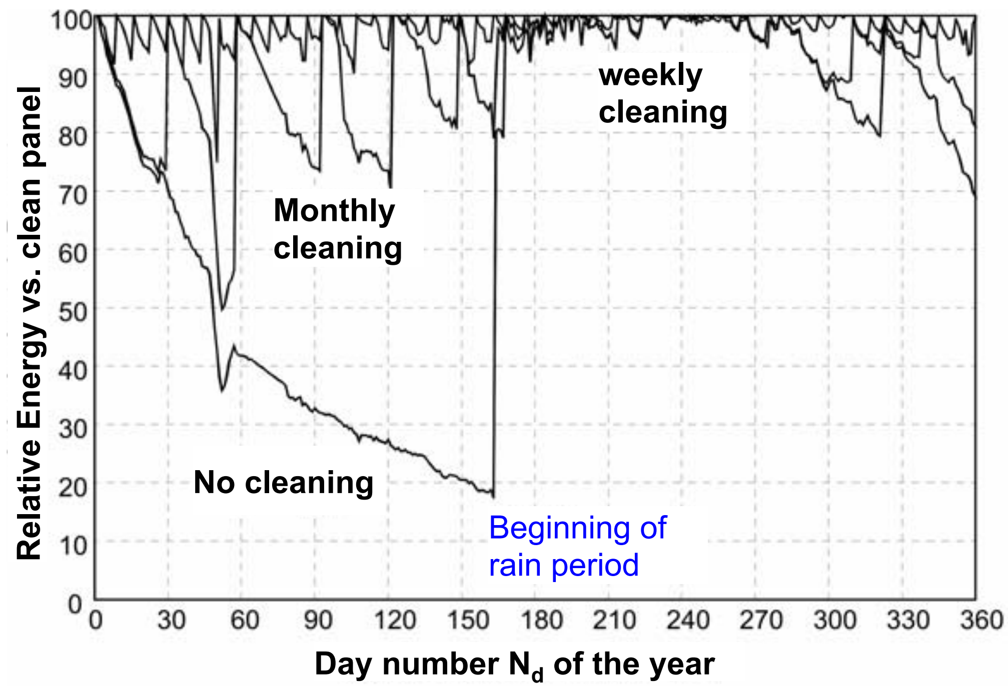


Fig. 4.24: Dirt & cleaning effect : experimental results [7] measured in 1989 Dakar (Senegal)

4.1.7 Sun-tracking systems

Sun-tracking systems can be subdivided in one-axis (tilt axis) and two-axis (tilt and azimuth axes) systems (see fig. 4.25). From a theoretical point of view, it seems evident that two-axes sun-tracking systems seem to have the ability of substantially increase the PV solar power, ensuring throughout the whole daytime an almost constant incidence factor $\cos\theta_Z$.

As shown in fig. 4.26, the power versus time diagram shows an almost rectangular shape from sunrise to sunset time, at least for "clear sky" weather conditions.

Unfortunately, this encouraging fact is somehow counterbalanced by other "reality-based" elements:

- **Under "cloudy" weather conditions, the energy gain might be close to zero or even negative.**

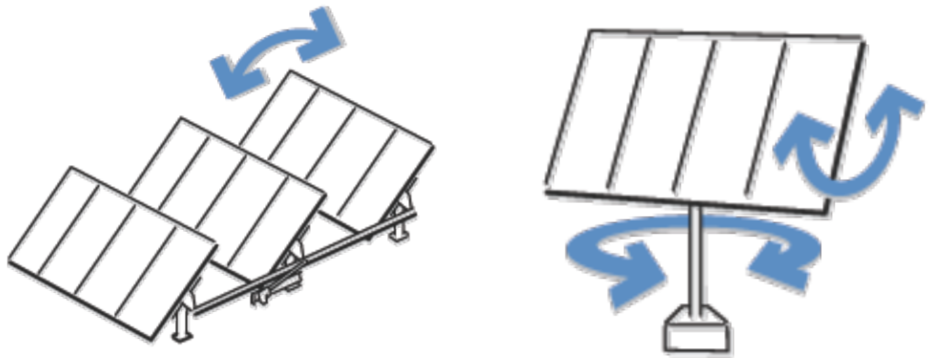


Fig. 4.25: One-axis (left) and two-axes tracking systems

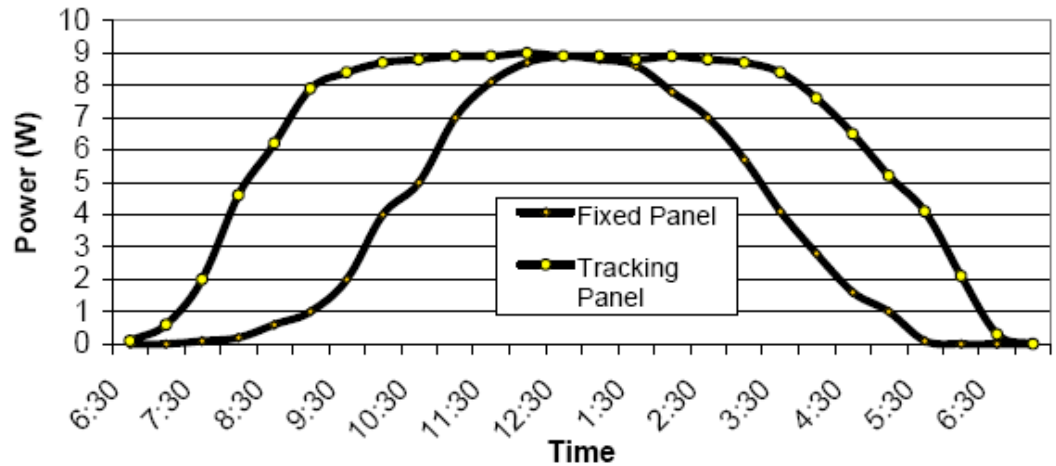


Fig. 4.26: PV power comparison fixed and sun-tracking system

- **In countries or locations having a high diffused radiation component, the optimal incidence angle for the direct radiation is not compatible with the optimal diffused (and reflected) irradiation angle (see also fig. 4.21).**
- **The resulting monthly mean PV energy gain varies between 5% to 50% (see fig. 4.27), depending on the AM conditions.**
- **Considering the 1 to 4 cost ratio between PV panel and tracking system, an over-all energy increase of <25% is economically not profitable.**
- **The resulting loss of active area in sun-tracking systems (see fig. 4.28), results also in a loss of PV energy/area coefficient.**

The above mentioned points make the sun-tracking system less attractive, (or even non-profitable) for many european regions.

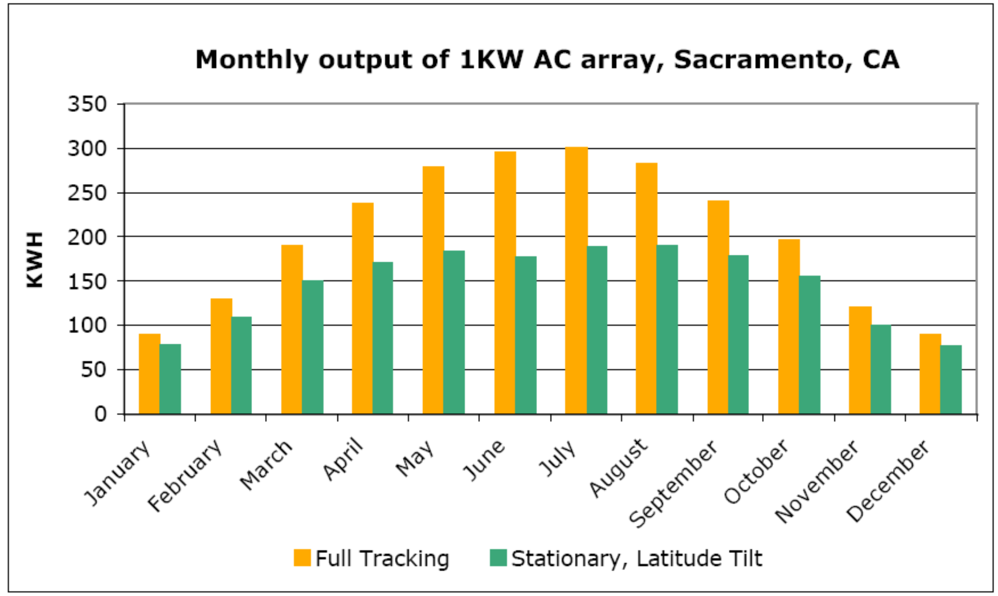


Fig. 4.27: PV energy output comparison stationary vs. tracking (2 axes)

Fig. 4.28: Illustration of area loss of sun-tracking systems

4.2 System Parameters & performance index

4.2.1 Mechanical & Electric installation components

Apart from the calculation methods for the estimation of the available solar irradiation, the design of a PV System should also take care or (basic) mechanical and electric aspects of the installation. Usually, these components represent about 20% of the total investment costs.

For a typical household system the available surfaces need to be analysed in size, inclination angle and orientation.

Fig. 4.30 shows some (simplified) orientation coefficients (in %) of surfaces with different orientations. The tilted surfaces are supposed to have an inclination angle of 30°.

The PV panel are commonly mounted on mounting rail systems (see fig. 4.31) and fixed with appropriate fixing angles.

The mounting rails need not only to support the weight of the PV panels, but also to resist on wind effects and snow weight in winter (details see annex 8.2).

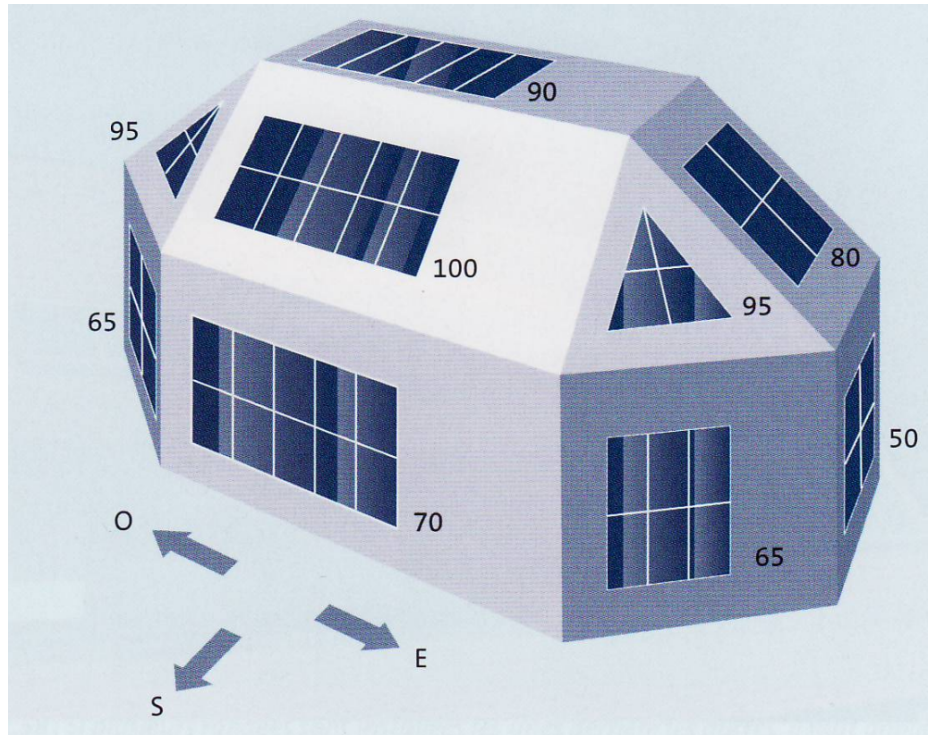


Fig. 4.30: Surface orientation and orientation coefficients

- « rooftop » pannels are mounted in « **sheds** » (fig. 4.33)
  - The sheds (tilted pannels) are sufficiently spaced to avoid a excessive shadowing from one row to the next one.
  - An **inclination angle of 18°** represents (in Switzerland) a good compromise between shadow losses and occupation ratio

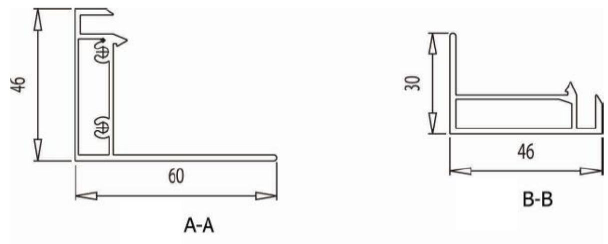


Fig. 4.31: Frail mounting & fixation system

- For any configuration:
  - **Sort out the pannels** having the same (or similar) exposition (PV current) to be connected in series to avoid excessive mismatch .
  - Limit the **cabling losses to 1-2%** (or lower).

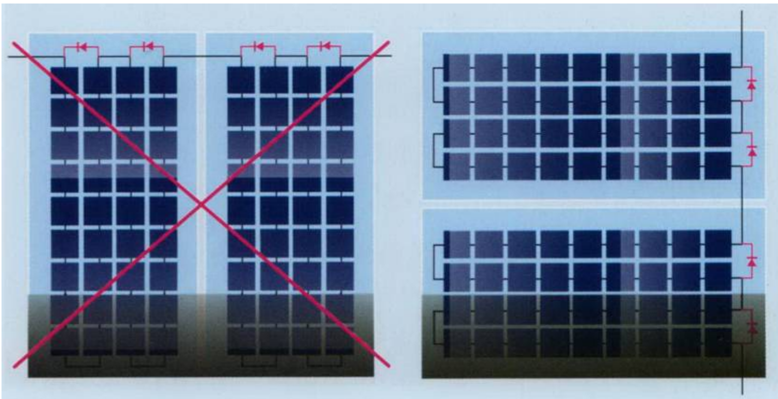


Fig. 4.32: Shadow effect on modules in series

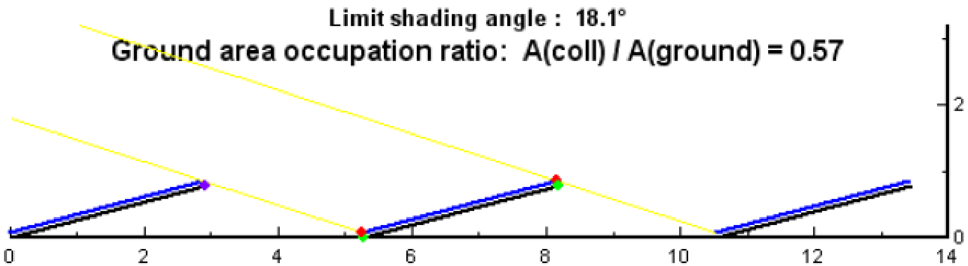


Fig. 4.33: sheds with 18° inclination and needed spacing

Fig. 4.35 shows a typical electric connection architecture for a household PV system with battery backup.

The AC connecting switch, ensuring also the anti-islanding protection of the system, allows either :

- **the battery charging and/or load powering through the PV AC system (grid independent functionality)**
- **The connection to the AC grid with PV power injection (grid dependent connection)**

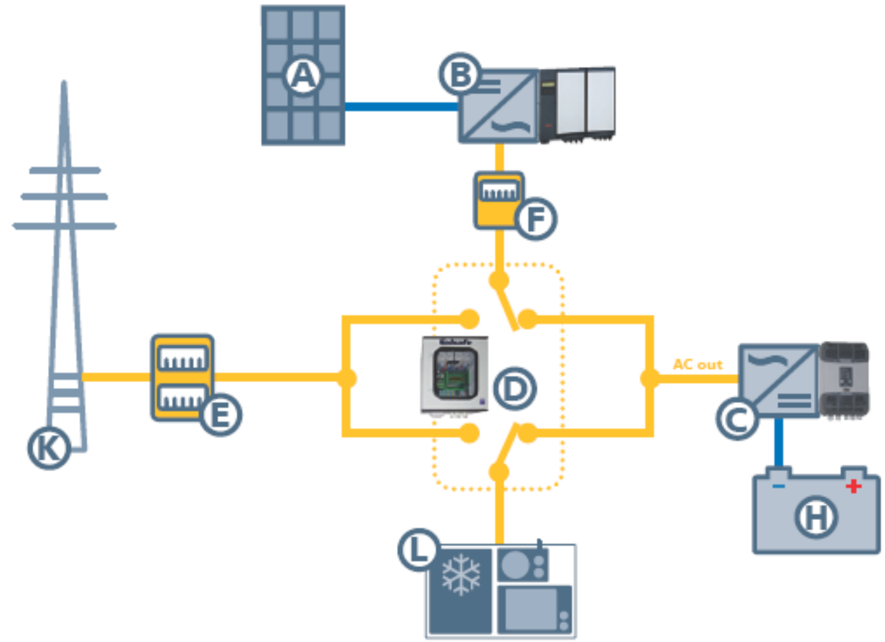


Fig. 4.35: Household PV AC System with battery backup: A: PV panel; B: connection box & inverter; C: battery AC/DC converter; D: AC connecting switch; E: bidirectional counter; F:unidirectional counter; H: Battery; L: load

This type of installation allows to inject PV energy into the AC grid without charging (discharging) losses through the battery. This connection scheme allows also to limit the cable losses, as the equipment is connected on the AC line (higher voltage). The battery charge is controlled by the AC/DC converter (equipment C in fig.4.35), which acts as an inverter (discharging) or rectifier (charging).

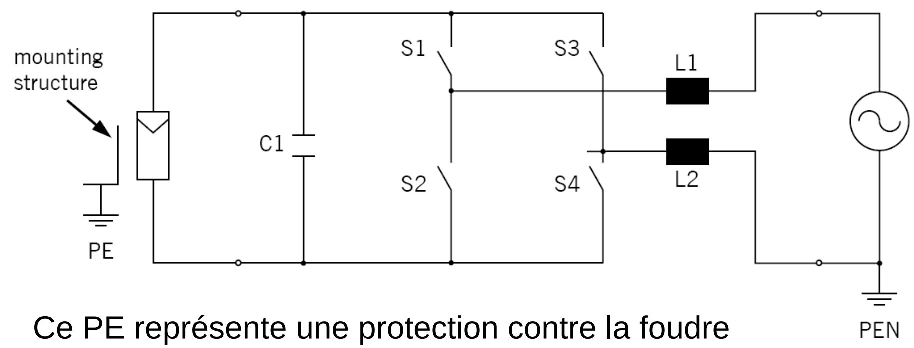
4.2.2 Grounding & Lightning protection

To ground or not to ground is not the question, the question is rather how to do it. For applications using a transformer-less inverter, both polarities (+ and -) of the PV DC outputs must remain isolated from earth ground (fig. 3.36).

In case of an inverter, isolated from the AC network (50 Hz or HF transformer), the DC outputs of the PV generator my be connected to earth ground at one end (fig. 4.37) or "centrally tapped" to earth.

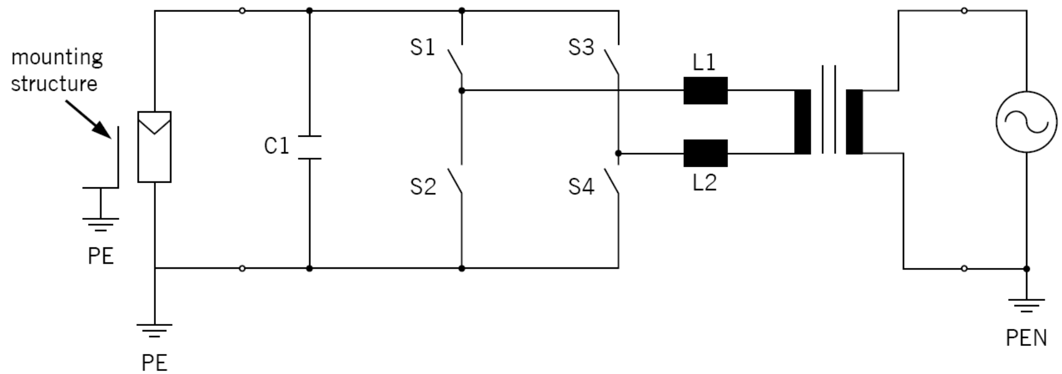
In both cases, the PV mounting structure needs to be connected to earth.

In addition, grounding protections (leakage current detection or FI-type protections) need to be installed to prevent from any hazard due to grounding or isolating failures.



Ce PE représente une protection contre la foudre

Fig. 4.36: Grounding with transformer-less inverter



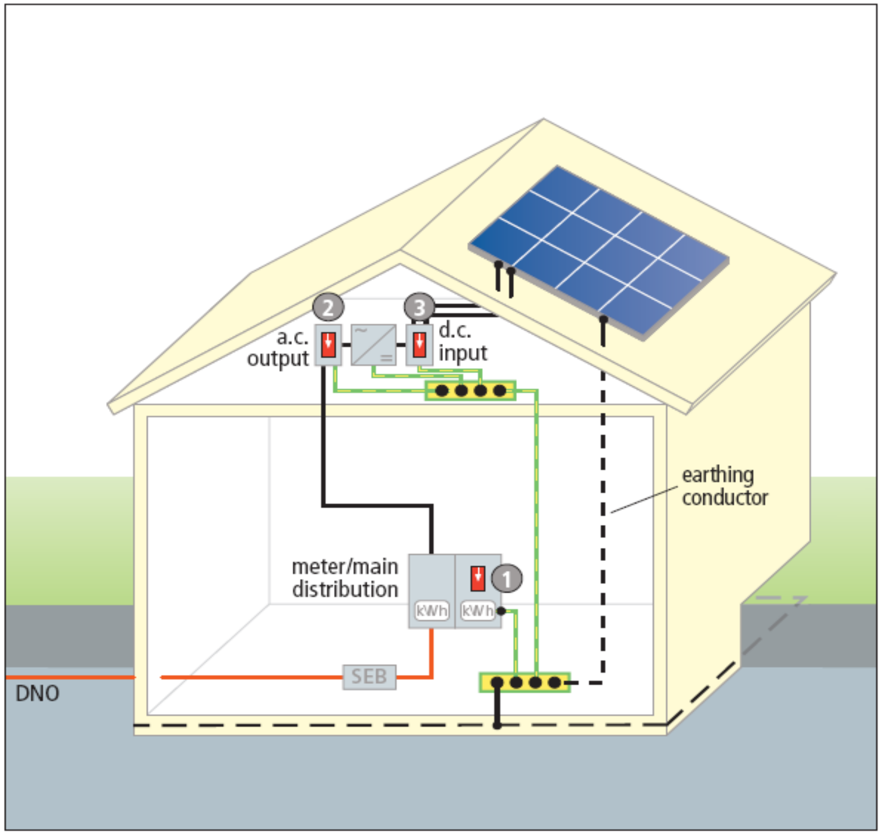
isolation galvanique

Fig. 4.37: Grounding for inverter with galvanic separation

To protect the system from surge voltages (or currents) induced by (nearby) lightning impacts, (lightning) surge supressing devices should be installed.

The figures below show the installation of surge supressing devices for a household PV system with or without lightning protection rods. The maximum tolerated distances are valid for EU countries.

Le circuit rouge représente le para-foudre



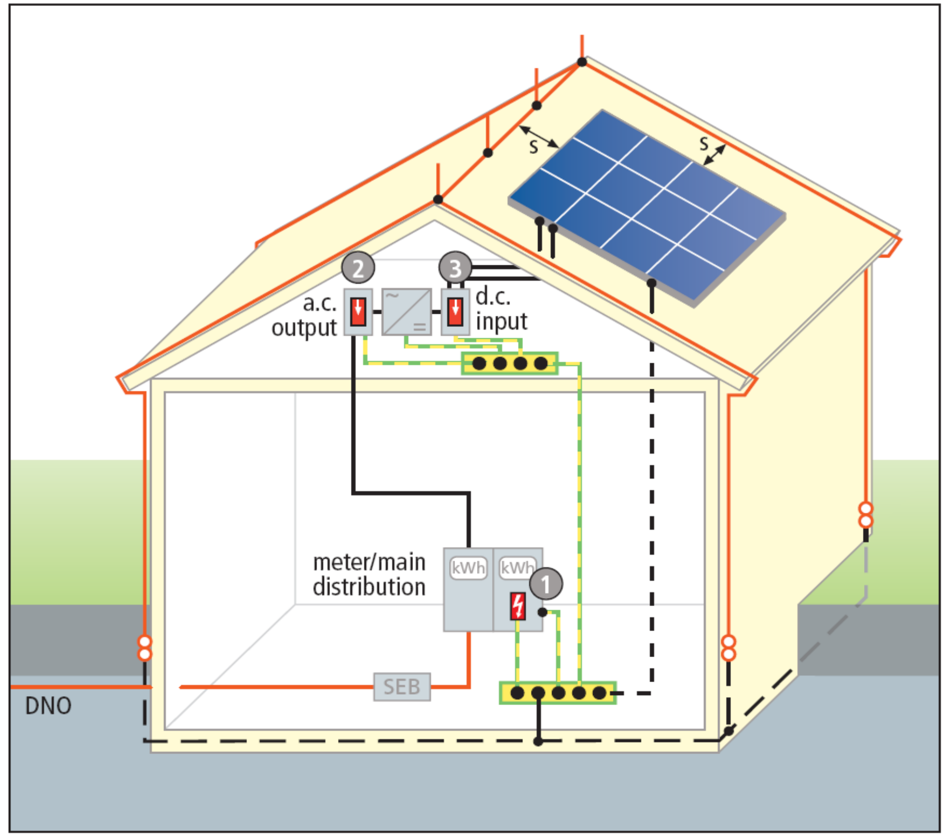


***Fig. 4.38**: **Household Grounding** without (left) & with **Lightning protection** (right): 1: mandatory if $N_g > 2.5$; 2: mandatory if distance to distribution > 10m; 3: mandatory if distance to PV panel > 10m; s : distance metal conducting parts to PV panel housing according EN62305-3*

The figure below shows the installation of surge supressing devices for a typical PV plant system.

Apart form the surge protecting devices and the lightning rods, the system shall also be grounded with a earth grounding mesh, covering the entire PV plant, with a mesh size of < 20m x 20m.

The metal supporting frames (with the PV panel fixed onto) have to be earthed every 10m of length.

Acquisition units for the measurement of physical parameters (wind, temperature, etc.) shall also be adequately protected with surge supressing devices.

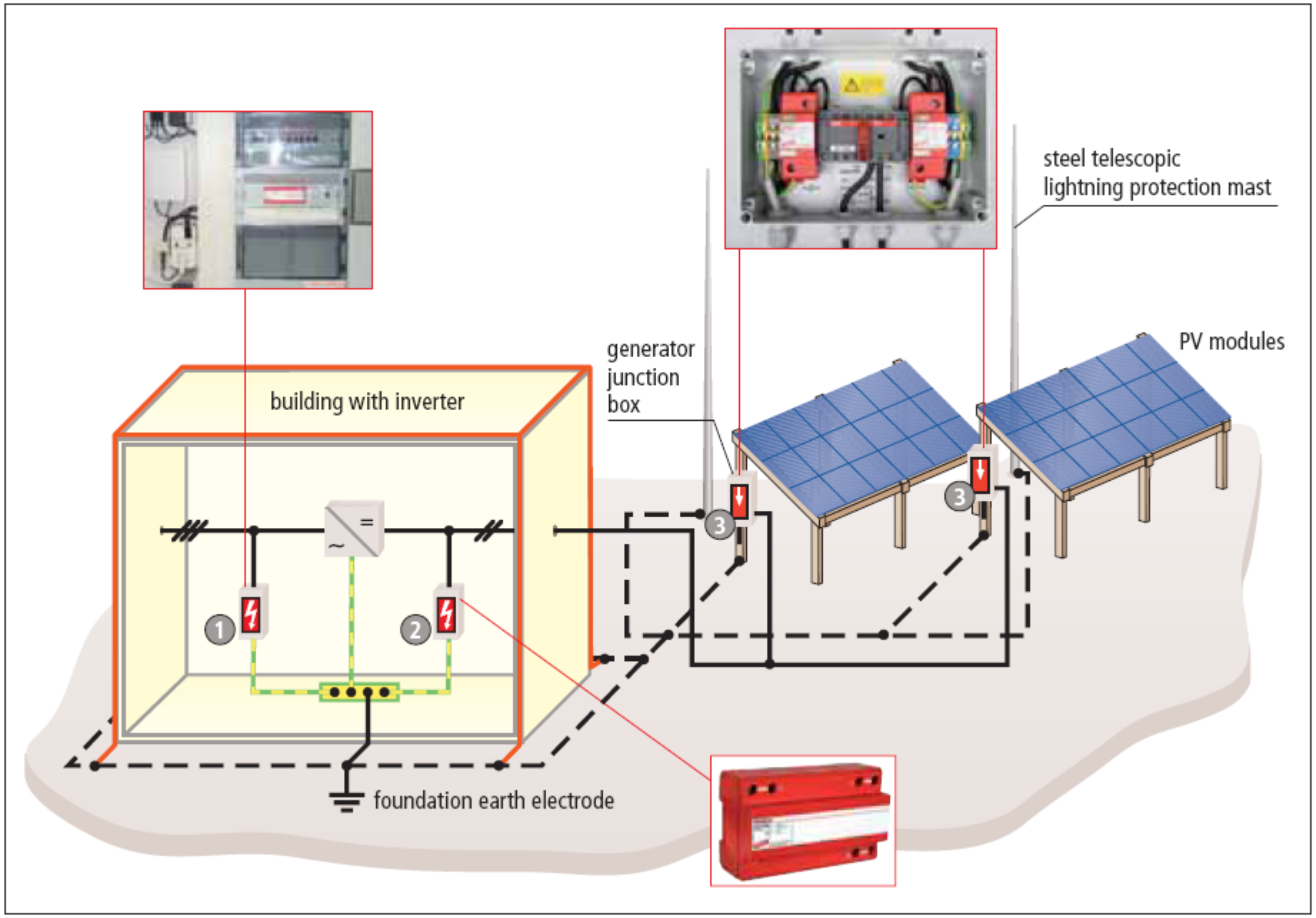


***Fig. 4.39**: **PV Plant Grounding** & **Lightning protection**: 1: AC output surge protection; 2: DC inverter input protection; 3: output protection for each PV module.*

Pour l'onduleur, on faut le choisir de façon à ce que les plages de fonctionnement pour la tension et le courant soient entre les valeurs supportées par l'onduleur. Il ne faut pas choisir un onduleur trop gros car ça coûte cher pour rien

DC/DC and DC/AC converters have to be adequately chosen in order to comply with the following main design parameters:

- **The (DC) input voltages have to be in accordance with the voltage variation of the considered PV modules used (or eventually with the battery voltage variation).**
- **The current rating has to support the max available PV current (I_{sc})**
- **The MPPT algorithm of the inverter has to support the MPP voltage variation of the PV generator (MPP voltage window matching : see also §4.2.3)**
- **The maximum supported power of the inverter has to be compatible with the max. power of the PV generator. Furthermore the inverter (and transformer) needs to supply the corresponding max. reactive power (Q_{max}) (see also §3.3.1 and exercise 4 of part 3).**
- **The converter (or battery charge controller) used to charge the battery has to be compatible with the charge current and voltage requirements of the battery.**

DC/AC inverters inverters connected to the AC grid, have furthermore to be compatible with the existing grid codes (see also §3.3.6 and § 3.4.3):

- **The THD generated by the inverter has to comply with the power quality requirements**
- **The power factor (cosφ) of the injected AC power has to comply to the local grid code requirements**
- **The "Anti-islanding" algorithm of the system has to comply with the failure voltage-to-time requirements**
- **Power generation limitations (due to frequency- and voltage-variations on the grid) have to be respected.**

En généra, on prend PR=0.75

4.2.3 Energy Yield and performance

The over-all energy performance index of a PV power plant can be expressed by the performance ratio PR of the system, which is:

$$PR = \frac{E_{AC}}{\frac{G_y(s,a)}{G^*} \cdot P^*_{MPP}} \qquad \textbf{(Eq. 4.20)}$$

where:

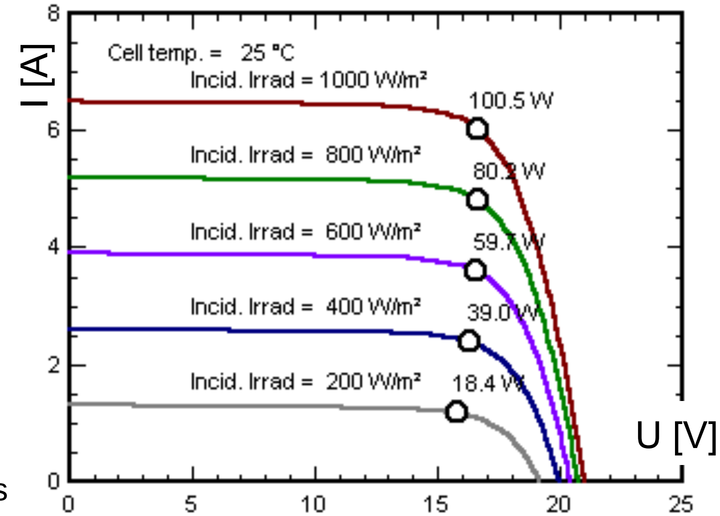
- **E_{AC} in [kWh] is the energy injected into the AC grid**
- **$G_y(s,a)$ in [kWh/m^2] is the yearly mean radiation for a PV generator with tilt angle s and oriented at azimuth angle a**
- **G* is the STC nominal irradiance = 1000 [W/m^2].**
- **P^*_{MPP} is the max. power, in [kW], generated by the PV array under STC conditions**

The performance ratio depends on the individual efficiencies of the elements (PV panel, cabling inverter,..) present in the power flow of the PV power plant. The mean european efficiency η_{EUR} of an inverter (see §3.3.5) is a common way to take into account the variability of the inverter's efficiency.
The PV panels are characterized by STC (Irradiance 1000W/m^2, cell temperature of 25°C) and NOTC (cell temperature with ambient air temperature of 20°C and irradiance of 800W/m^2) values, which are usually not encountered under real operating conditions.
As the cell temperature influences the open-circuit voltage (V_{OC}) and the irradiance the short-circuit current (I_{SC}), both need to be taken into account for the estimation of the effective MPP of the PV panel.

The I_{sc} value can be estimated with:

$$I_{SC}(G) = \frac{I^*_{SC}}{G^*} \cdot G_{eff} \qquad \text{(Eq. 4.21)}$$

where:
- **I^*_{SC} and G^* are the STC short-circuit current and irradiation values**
- **G_{eff} is the effective encountered irradiation**



The V_{OC} is cell temperature (T_c) dependent:

Ns : nombre total de cellules.

$$V_{OC}(T_C) = V^*_{OC} - \left(T_C - T^*_C\right)\cdot\left(N_S \cdot 2.3\,mV/°C\right) \qquad \text{(Eq. 4.22)}$$

Ce terme est à repérer avec les unités

The cell temperature (T_c) can be estimated with the ambient air temperature (T_a):

$$T_C = T_a + C_t \cdot G_{eff} \qquad \text{(Eq. 4.23)}$$

Ta* : T ambiante

using:

$$C_t = \frac{NOCT[°C] - 20}{800[W/m^2]} \qquad \text{(Eq. 4.24)}$$

NOCT est donné par le fabriquant

If the NOCT value is unknown a good approximation for the C_t value is C_t = 0.03 [°C m2/W].

The cell temperature is also affecting the effective MPP power (P_{MPP}) of the PV generator with "cell efficiency coefficient" of approximately -0.4 [%/°C].

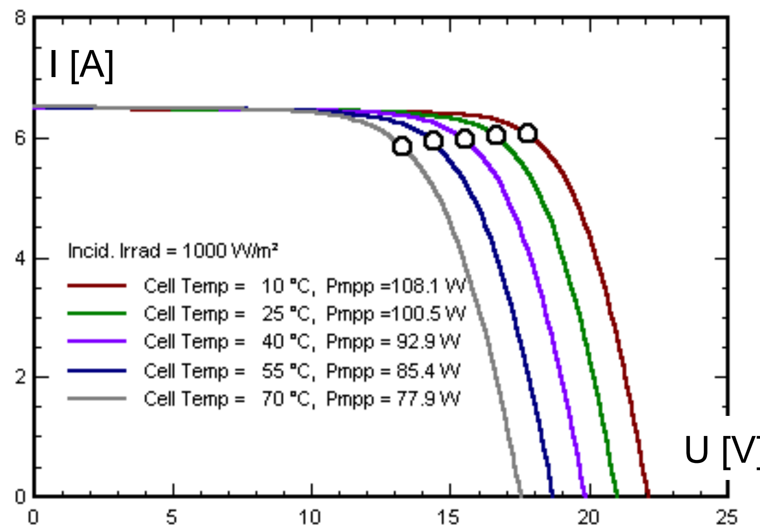


Fig. 4.40: Typical I-U curves for STC (above) & temperature depending (below)

0.004 est la déviation de la P par rapport à la température : température coefficient power
on prend cette valeur si on ne la donne pas pour le panneau

Pmax

$$P_{\mathcal{M}} \cong P_M^* \cdot \frac{G_{eff}}{G^*} \cdot \left[1 - \left(T_C - T_C^*\right) \cdot 0.004\right] \quad \textbf{(Eq. 4.25)}$$

P*M : puissance standard panneau

Other cell efficiency estimations use the wind speed (see fig. 4.41) and / or the form factor (FF) of the PV cell characteristics (see [4]).

$$FF = \frac{P_M^*}{I_{SC} \cdot V_{OC}} \qquad \textbf{(Eq. 4.26)}$$

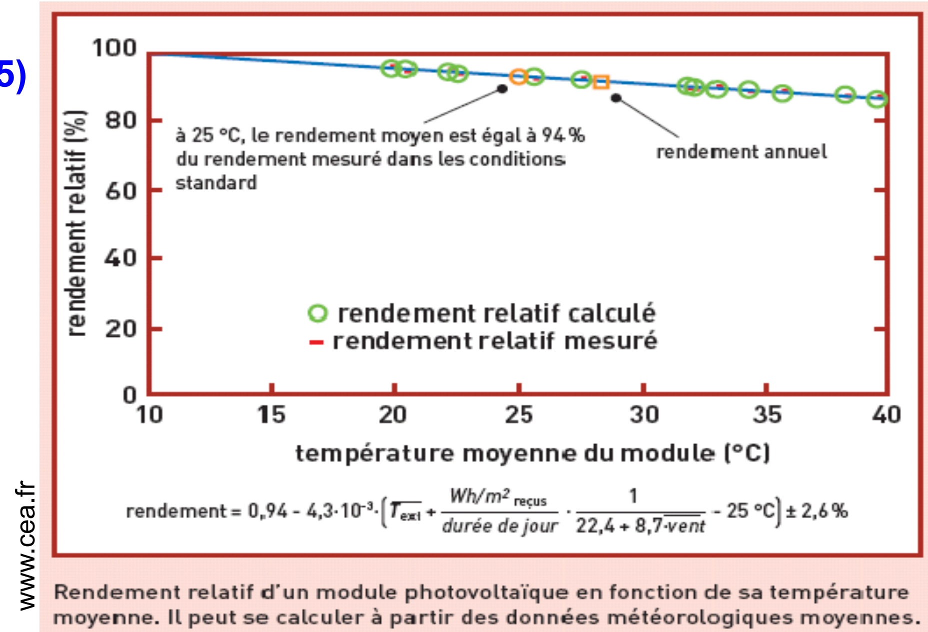


Fig. 4.41: Evolution of relative PV cell efficiency

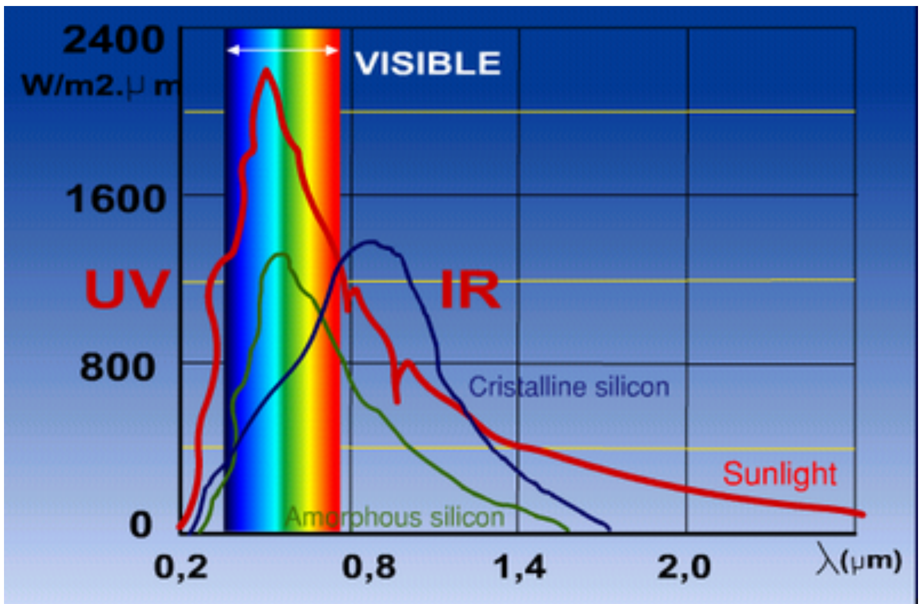


Fig. 4.42: STC & PV cell-type spectral density

Moreover, the cell efficiency also depends on the spectral density distribution of the irradiation G_{eff} (see fig. 4.42). Diffuse irradiation tend to be more in the "red" or "infra-red" light spectrum than direct radiations.

PV characteristic mismatch between each module or cell also have negative effects on the over-all MPP and efficiency.

4.2.4 MPP voltage window & system availability

Due to the variation of the temperature cell, the irradiation conditions and spectral density, the MPP power and its associated MPP voltage may vary considerably throughout the yearly encountered operating conditions.

As shown in Fig. 4.43, the MPP voltage may vary over a +/- 15% range throughout one year.

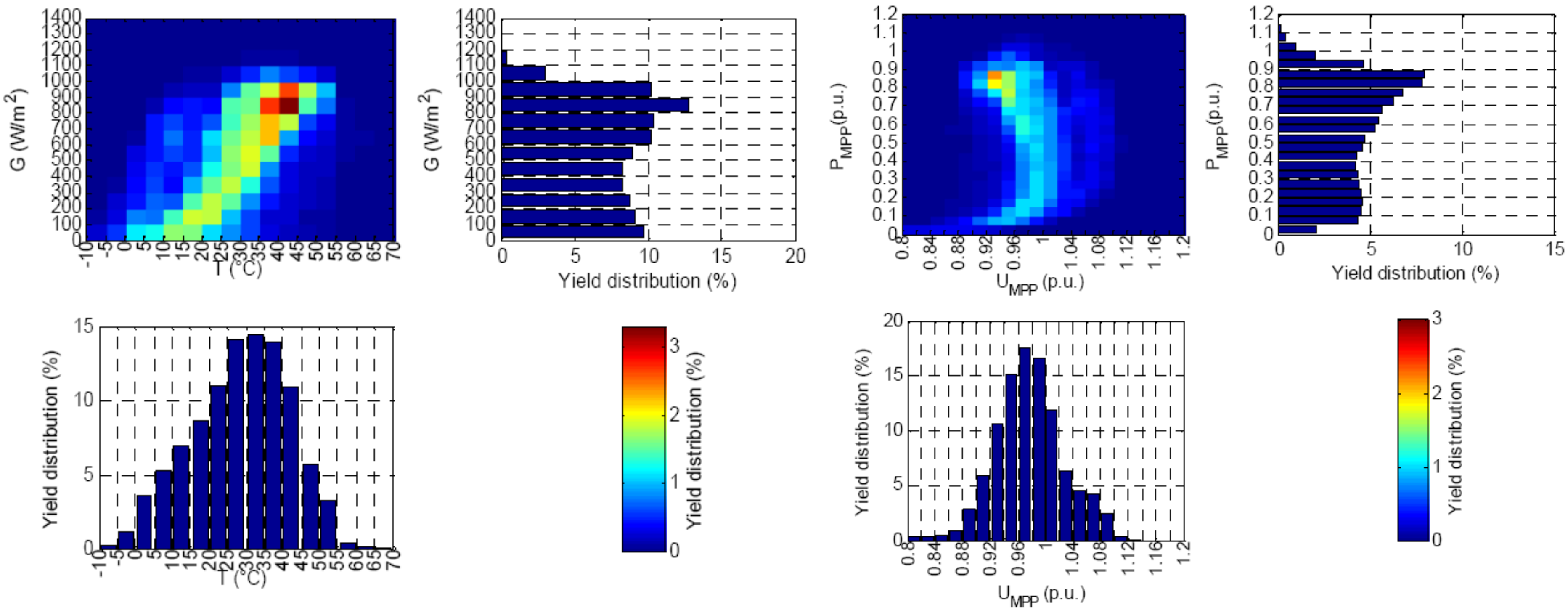


Fig. 4.43: Annual distribution of Irradiance G_{eff} (in W/m²), P_{MPP},U_{MPP} for a PV System in Vienna (Austria)

The inverter has to "support" this MPP voltage variation. Critical situations may occur, if the MPP voltage falls below the minimum voltage supported by the inverter: in this case the inverter is unable to inject PV power into the grid for these low-voltage MPP conditions. On the other hand, the inverter has to support also the maximum PV voltage encountered, which corresponds to the V_{OC} voltage at minimum ambient temperature (see Fig 4.44).

The loss of performance due to improper MPP voltage window matching may be more important than any converter or cabling loss in the system.

The MPP voltage window is rather "enlarged" when a high number of PV cells are connected in series. On the other hand, direct inverter, without voltage step-up input stage need a (relatively) high input voltage and have therefore low minimum MPP voltage tolerances.

Taking into account the different losses and effects described, the performance ratio PR of a system is:

- **usually between 0.6 and 0.75 (measured values)**
- **good if above 0.75**

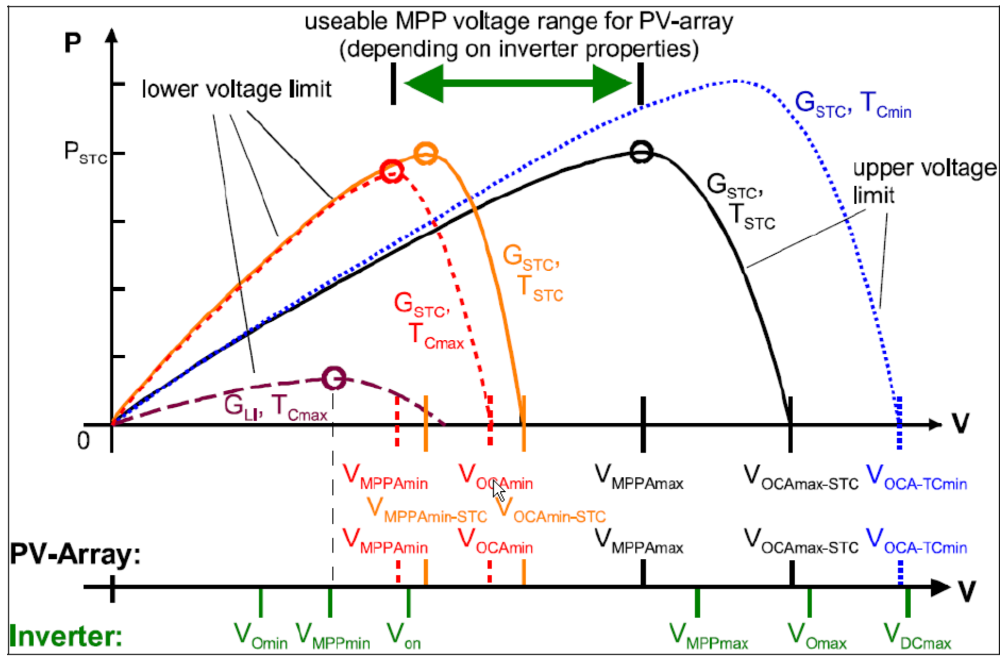


Fig. 4.44: V_{MPP}, V_{OC} and inverter voltage ranges

Another important system performance index is given by the availability (a) of a PV System. The availability (see also §3.4.2) is defined as 100%, when the generated PV power exceeds the requested power. In the other case, the availability is the ratio between requested and generated PV power. As the generated PV power (and energy) depends on the solar irradiation, the mean requested AC energy (E_{AC}) will be achieved with a mean solar irradiation G_{dim}, used for the design (dimensioning) of the PV System:

$$E_{AC} = \frac{G_{\dim}}{G^*} \cdot \frac{P_M^*}{A_{\mathrm{mod}}} \cdot A_{\dim} \cdot PR \qquad \text{(Eq. 4.27)}$$

Adim : surface installation

Where A_{dim} is the total surface area of the PV panels. Hence the availability of the system can be expressed as:

$$a(\mathrm{G_{eff}}) = \begin{cases} 1 & if\ G_{eff} > G_{\dim} \\ \dfrac{G_{eff}}{G_{\dim}} & if\ G_{eff} < G_{\dim} \end{cases} \qquad \text{(Eq. 4.28)}$$

The availability may be evaluated daily, weekly, monthly or yearly (a_d, a_w, a_m, a_y). Some references (see [4]) use the complementary value to the availability, the Loss of Load Probability LLP, with LLP = 1-a.

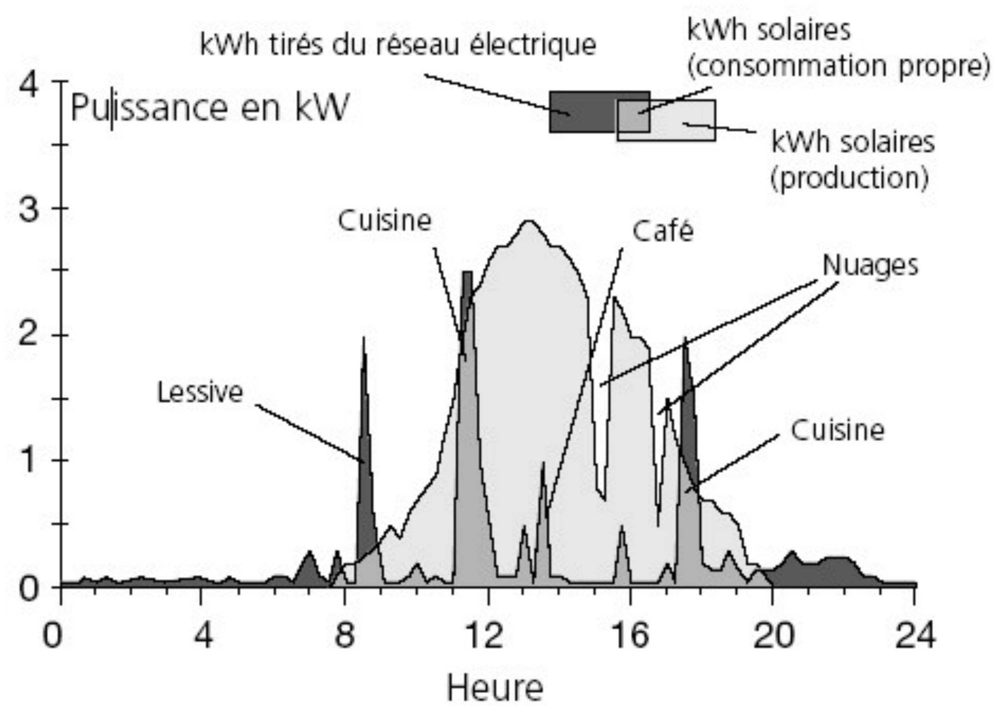


Fig. 4.45: Requested AC power vs. PV generated power

4.3 Economic Analysis of PV Systems

4.3.1 PV System Cost analysis

At the beginning of the project, it is useful to evaluate the needs (PV panel area, total power, min. and max. voltages) with a pre-design of the system. The accuracy of the energy and power yields may then be increased with a SW designing tool (like "PVSyst " or others). The main parameters to be evaluated during the pre-design are:

- Total PV panel surface area estimated, based on
  - The energy needs by the user or customer
  - Irradiation rates available for the concerned location
  - Available inclination angle (roof surfaces) and azimuth orientation
  - Rough estimation of the system performance ratio expected
- Electric parameter estimation, namely
  - The maximum available (or needed) power
  - Minimum and max. voltages and currents

Once these technical parameters are known, the economic evaluation of the pre-design can be started:

- Estimation of energy cost (or economic yield in CHF/kWh), based on
  - The estimation of investment and maintenance costs
  - The estimation of total energy produced
  - The estimated life-time or paying-off time (usually 15 to 25 years) and interest rates

The estimation of the investment costs, can be either:

- **Based on quotations for the different needed components (PV panels, inverter, cabling…)**
- **Based on rough system prices : for Switzerland the actual system costs will be between 2.0 to 2.6 kCHF/kWp (for > 100 kWp) and 3.0 to 4.0 kCHF/kWp (for < 10 kWp).**
- **Maintenance costs (except batteries) may be around 4 to 6 cts/kWh or the equivalent to the inverter investment costs**

Based on the total investment costs (C), the annual instalment (A) can be estimated based on the pay-off time (n years) and the interest rate (i):

$$A = C \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \qquad \text{(Eq. 4.30)}$$

Once the yearly costs are known, the energy cost rate (SFr/kWh) can be established.
Finally, knowing the applicable feed-in rates, the yearly profit and the return of investment (ROI) may be estimated with:

$$ROI = \frac{profit}{investment} \qquad \text{(Eq. 4.31)}$$

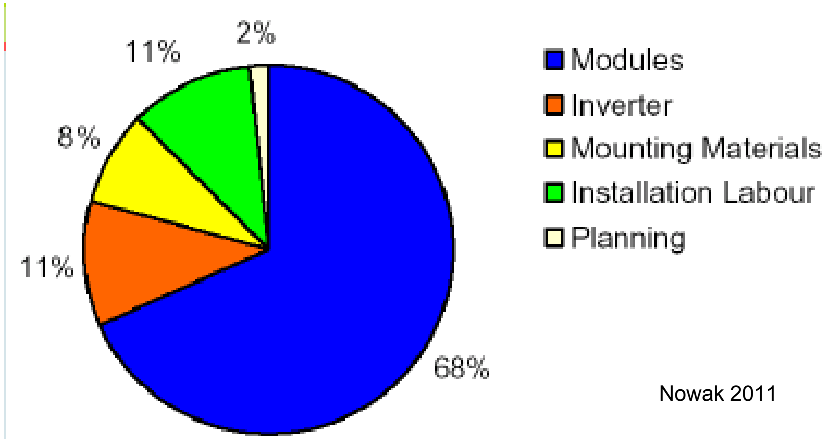


Fig. 4.46: Typical investment cost budget

Some interesting facts and stats may be of interest for the pre-design:

- **The mean yearly energy budget of a swiss household (4 people) is about 4000 kWh (without heating nor warm water generation). An "economic" family will use 1000 kWh less.**
- **In Switzerland , one square meter of PV cells will produce yearly an AC energy of 90 to 180 kWh, corresponding to a peak power of 100 to 200 Wp. *1/3* of this energy will be produced during the winter months and the remaining *2/3* during the summer months.**
- **Every kilowatt of PV peak power installed (kWp), corresponds to a yearly yield of 800 to 1000 kWh. In well exposed locations, this value may rise to 1200 kWh.**
- **A typical swiss household will consequently need a PV system with 3 kWp to 4 kWp peak power for a PV cell surface area of 15 – 40 m^2 to cover its electric energy budget.**
- **A reasonable approach could be design a PV system, covering "only" the "non-renewable" energy part of the (electric) energy budget. This helps to lower down the initial investment costs without taking any unconsidered part of "risk". Actually, the "non-renewable" (nuclear) energy part in Switzerland represents about 40% of the total consumed electric energy. As any PV system will hardly achieve a 100% availability, this approach still ensures a full availability, a possible power peak shift and a reasonable contribution to the development of the renewable energies.**

- **As shown by the figure below, the PV module price is reduced by approx. 22%, each time the production is doubled.**

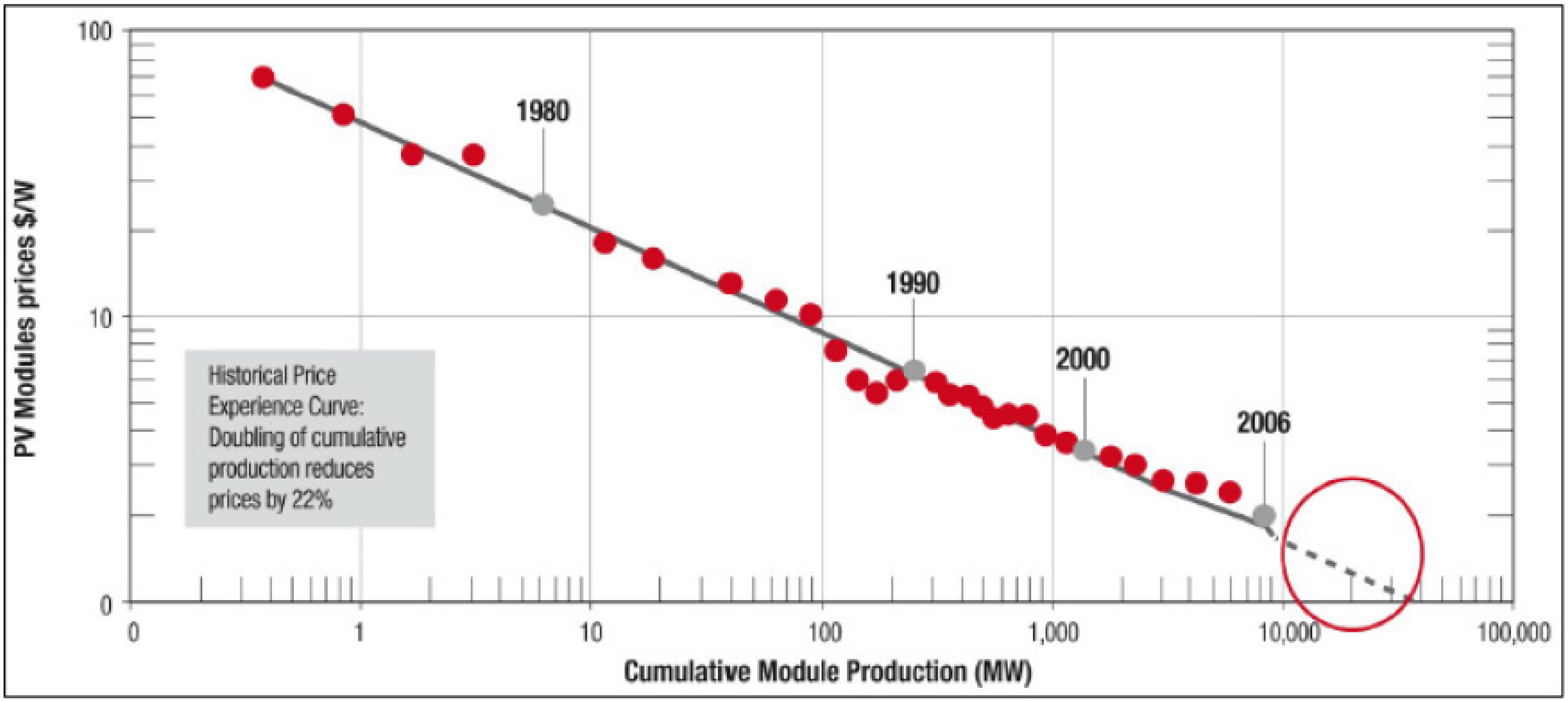


Fig. 4.47: Cost trend of PV module prices Source SETfor 2020 A.T. Kearney 2009

4.3.2 Feed-in tariffs & Energy costs

Actually, there are 2 different incentives for PV installations in Switzerland:

- **Fixed feed-in tariffs (FIT) established by the "SFOE" (Swiss Federal Office of Energy).**
- **Federal & local Tax reduction for renewable energy projects.**

Taux de rétribution valables pour les nouvelles décisions
incl. TVA 8%

Catégorie d'installation Classe de puissance	Taux de rétribution 2011 [ct./kWh]	Taux de rétribution à partir de 1.3.2012 [ct./kWh]	Taux de rétribution à partir de 1.10.2012 [ct./kWh]	Taux de rétribution à partir de 1.1.2013 [ct./kWh]	Taux de rétribution à partir de 1.1.2014 [ct./kWh]	frais de référence 2014* coût d'investissement CHF/kW	 frais d'entretien ct./kWh
Isolée ≤10 kW	42.7	36.5	33.1	30.5		3015	6.0
≤ 30 kW	39.3	33.7	27.0	24.8	23.8	2295	6.0
≤ 100 kW	34.3	32.0	24.8	22.8	19.8	1980	6.0
≤ 1000 kW	30.5	29.0	23.1	21.3	19.2	1821	5.0
> 1000 kW		28.1	21.6	19.9	17.2	1724	4.5
Ajoutée ≤10 kW	48.3	39.9	36.1	33.2		3350	6.0
≤ 30 kW	46.7	36.8	29.4	27.0	26.4	2550	6.0
≤ 100 kW	42.2	34.9	26.9	24.7	22.0	2200	6.0
≤ 1000 kW	37.8	31.7	25.1	23.1	21.3	2023	5.0
> 1000 kW		30.7	23.5	21.6	19.1	1916	4.5
Intégrée ≤10 kW	59.2	48.8	42.8	39.4		3853	6.0
≤ 30 kW	54.2	43.9	36.5	33.6	30.4	2933	6.0
≤ 100 kW	45.9	39.1	33.2	30.5	25.3	2530	6.0
≤ 1000 kW	41.5	34.9	31.5	29.0	21.3	2326	5.0
> 1000 kW		33.4	28.9	26.6	19.1	2203	4.5

Source: Ordonnance sur l'énergie, appendice 1.2 (OEne, 730.01)

Fig. 4.48: Feed-in tariffs SFOE

The indicated FIT (see fig. 4.48) are granted for the entire life cycle of the PV installation, once the installation has been officially registered.

Due to the fact that the PV investment costs are continuously going down (see fig. 4.47), the SFOE is continuously adapting the FIT.

The FIT (in cts/kwh) are decreasing with the installed peak power (expressed in kWp). For a freestanding 50 kWp installation, the FIT (for 2014) can be calculated with following approach:

$$FIT = 60\% \cdot 23.8 + 40\% \cdot 19.8 = 22.2 \; {}^{cts}\!/_{kWh}$$

The economic profit may the be calculated with:

$$profit = E_{AC} \cdot (FIT - ECR) \qquad \textbf{(Eq. 4.32)}$$

where:

- **E_{AC} is the yearly produced AC energy**
- **ECR is the Energy cost rate**
- **FIT is the feed-in tariff**

The energy cost rate (ECR) is the sum of the annual instalment (A) and the annual maintenance costs (AMC) of the installation, versus the yearly AC energy produced:

$$ECR = \frac{A + AMC}{E_{AC}} \qquad \textbf{(Eq. 4.33)}$$

Based on political decisions taken in June 2013, following changes will apply for Switzerland in 2014:

- **Fixed feed-in tariffs (FIT) established by the "SFOE" (Swiss Federal Office of Energy) remain valid for installations, having a peak power capacity > 30 kWp.**
- **For small installations (2 kWp ≥ P_{max} < 10 kWp), an initial incentive of the investment cost is foreseen.**
- ***For installations with a peak power between 10 kWp and 30 kWp, the owner has the choice between a fixed FIT and an initial incentive.***
- ***Mini- and micro-power installations (P_{max} < 2 kWp) will furthermore neither receive an initial incentive nor any feed-in tariff (FIT)***

The initial incentive depends on the installed peak power (in kWp) of the PV installation, according to the table shown in Fig. 4.49.

Example: a small roof-mounted household installation with an installed peak power of 8 kWp, may receive following initial incentive after installation in 2014:

$$incentive = 1400 + 8 \times 850 = 8200\ CHF$$

Montant de la rétribution unique				
	Les installations ajoutées et isolées		Les installations integrées	
Mise en service	contribution de base (CHF)	contribution liée à la puissance (CHF/kWc)	contribution de base (CHF)	contribution liée à la puissance (CHF/kWc)
Du 2014	1400	850	1800	1050
Du 2013	1500	1000	2000	1200
Du 2012	1600	1200	2200	1400
Du 2011	1900	1450	2650	1700
avant 31.12.2010	2450	1850	3300	2100

Fig. 4.49: Initial incentive for small PV installations in CH

The level of installed PV power (in Wp/ habitant) depends on the attractiveness of the FIT scheme established (see fig. 4.49).

Some EU countries have additional incentives to promote the BIPV (Building Integrated PV), with requirements obliging the owners of new building to improve the energy efficiency or to use a certain minimum amount of renewable energies.

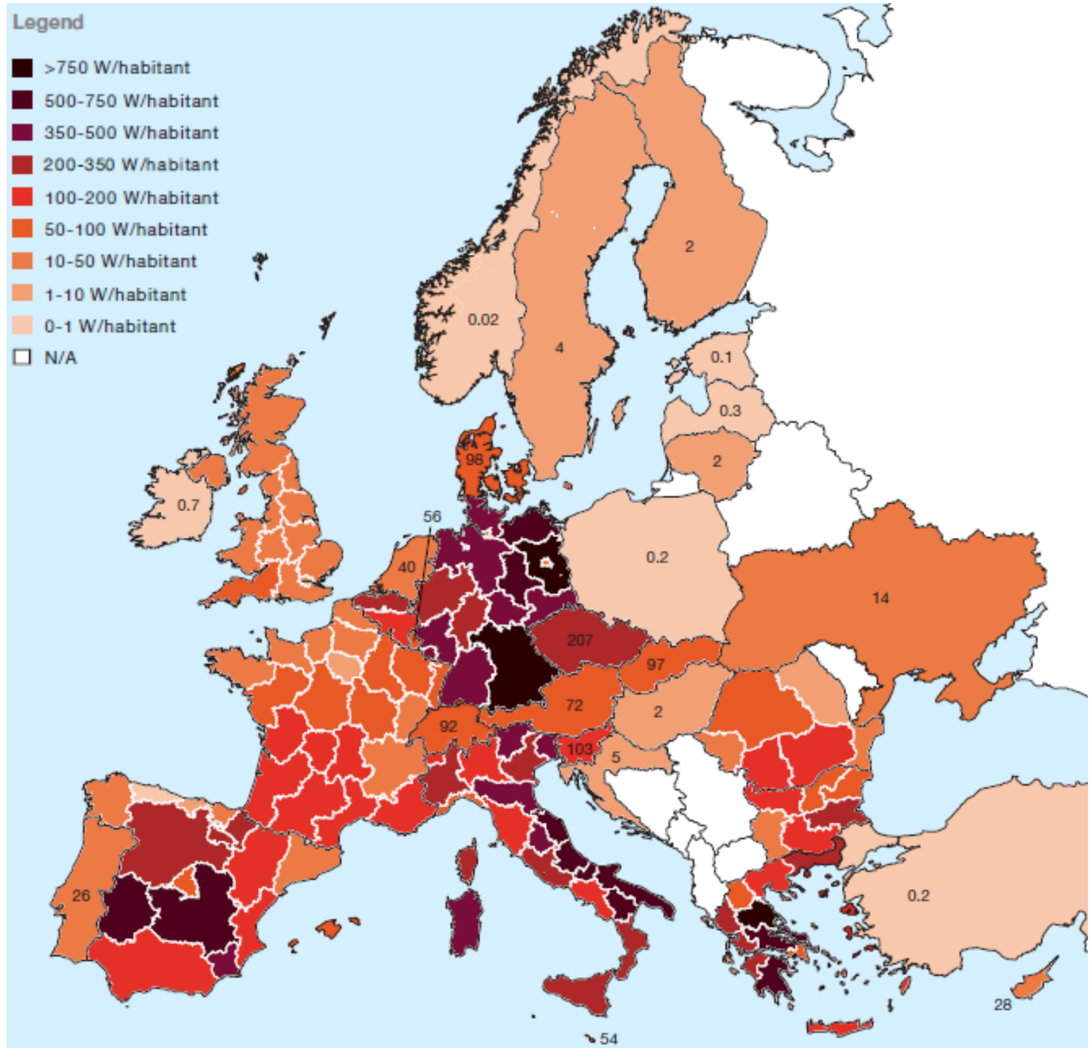


Fig. 4.50: PV installed power in Wp/habitant in EU (2013)

4.3.3 Life cycle Analysis & Energy payback

The energy payback is concept with increasing economic (and politic) importance. The energy payback time (EPBT) is defined as the ratio between the energy "input" used to cover the entire life cycle of the PV system and the mean energy produced by the PC system:

$$EPBT = \frac{E_{INPUT}}{E_{AC,\mathrm{Prim}}} \quad \text{(Eq. 4.34)}$$

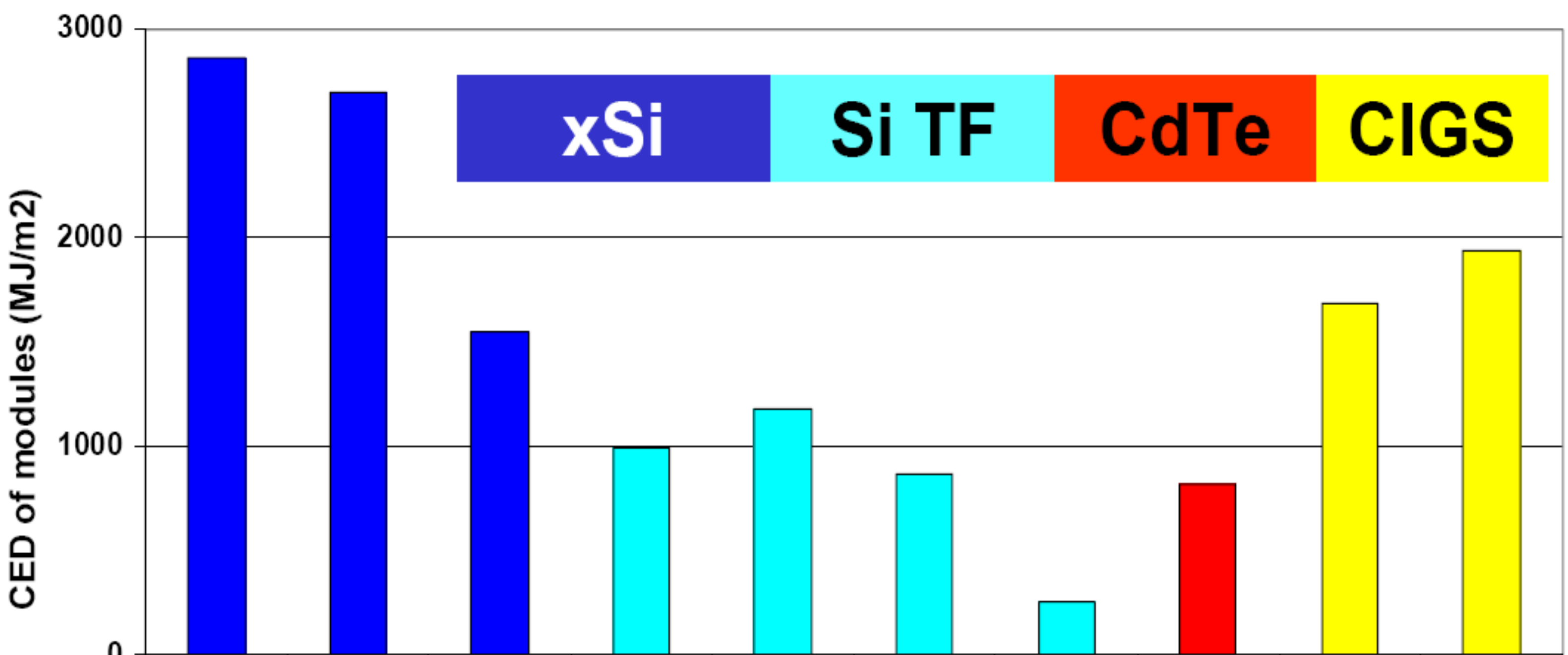
The life cycle assessment (LCA) or Life cycle analysis takes into account the cumulative energy demand (CED) for the production, transport and recycling of the considered cell technology.

The Fig. 4.50 shows a EPBT calculation example taking into account the mean primary energy needed by the electricity network supplier in Europe (UCTE european electricity mix). This latter may vary strongly from country to country.

E_{input} = Cumulative Energy Demand (CED) from LCA	12236 MJ_{prim}/kWp
Irradiation	1700 kWh/m^2.year
Performance ratio (IEC 61724)	0.75
Generated electricity	**1275** kWh/kWp.year
Efficiency electricity supply	**11.4** MJ_{prim}/kWh
Avoided energy	**1275 x 11.4 = 14535** MJ_{prim}/kWp.year
Energy payback time	**12236 / 14535 = 0.84 years**

Fig. 4.51: EPBT calculation example

The CED estimation depends on the cell technology considered. Fig. 4.51 shows the CED (in MJ/m^2) for various PV cell technologies. (Abbreviations: xSi : mono-crystalline silicon technologies; Si TF : Silicon Thin Film; CdTe : Cadmium Telluride cell; CIGS : Copper Indium Gallium Selenide)



	mono	multi	ribbon	a-Si	µm-Si	a-Si on steel	a-Si on PEN	CdTe	CIGS (1)	CIGS (2)
	2008	2007	2009	2008	2008	2006	2008	2009	2009	2007
	14.0%	13.2%	13.2%	6.6%	8.5%	5.7%	3.8%	10.9%	10.5%	11.0%
MJ/m2	2860	2699	1548	989	1173	866	252	811	1684	1936

Fig. 4.52: CED estimation example for various PV cells

Source: ECN Energy Research Center Netherland

The EPBT estimation depends as well as the CED on the cell technology considered. Fig. 4.52 shows the EPBT (in years) for various PV cell technologies (Abbreviations: see Fig. 4.51). Obviously the inverter, cabling and recycling part on the EPBT are more or less technology-independent.

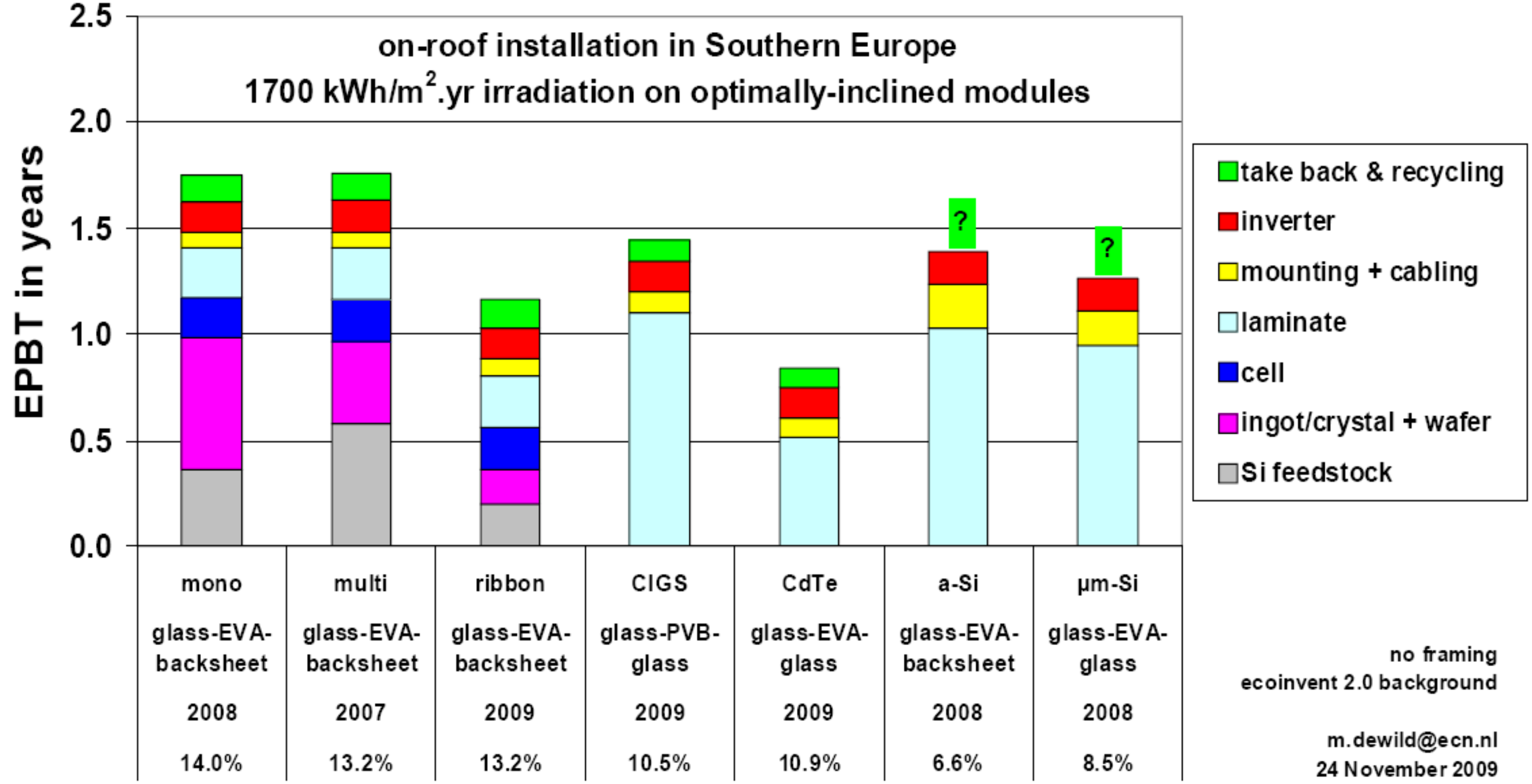


Fig. 4.53: EPBT estimation example for various PV cell technology Source: ECN Energy Research Center Netherland

The EPBT varies for a given technology also in function of the irradiation. The figure below shows the EPBT estimated for a 3kWp on-roof installation with optimal inclination angle.

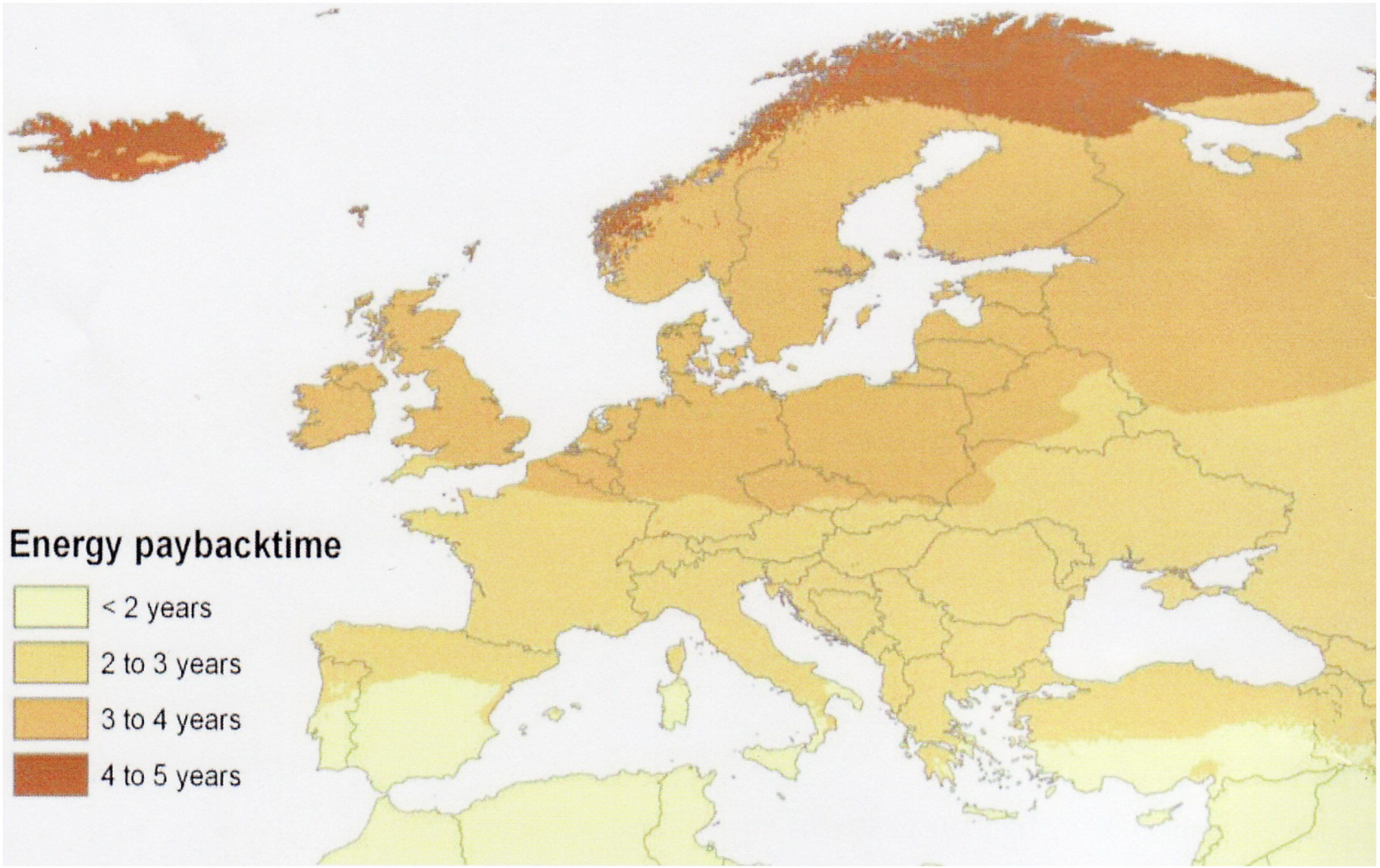


Fig. 4.54: EPBT in Europe (for given technology)

Sources: ESU services, base Ecoinvent

The Recycling of used or end-of-life PV cells plays not only an important matter in the EPBT, but represents also a growing industrial market. The PV cells may be either recovered (Fig. 4.54) or the different materials may be recycled after undergoing a thermal process (600°C).

The european "PVcycle" association (www.pvcycle.org) regroups over 30 PV cells manufacturer and aims to create a PV recycling channel for european countries until 2015.

Actually the recycling rates are of:

- **100% for metallic parts (aluminium, copper)**
- **95% for glass components**
- **75% for silicon parts**

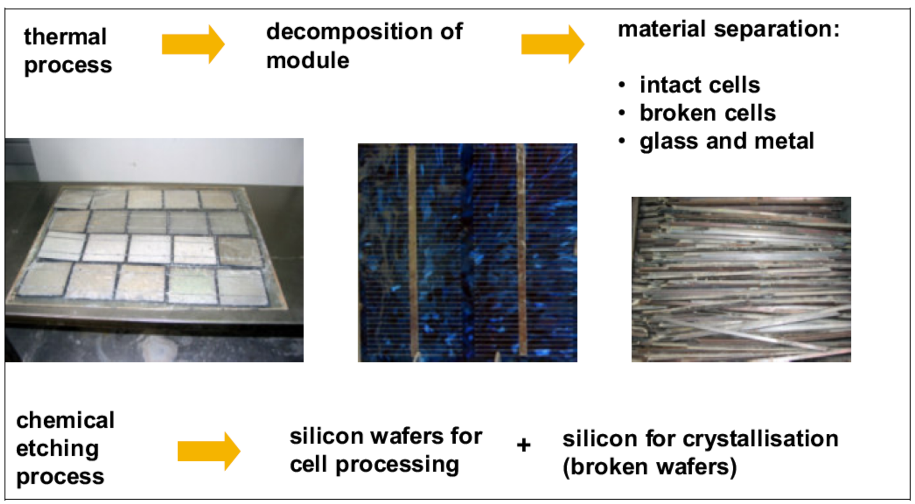


Fig. 4.55: Material recycling with thermal process

Sources: BMU, EPIA & BSW-Solar

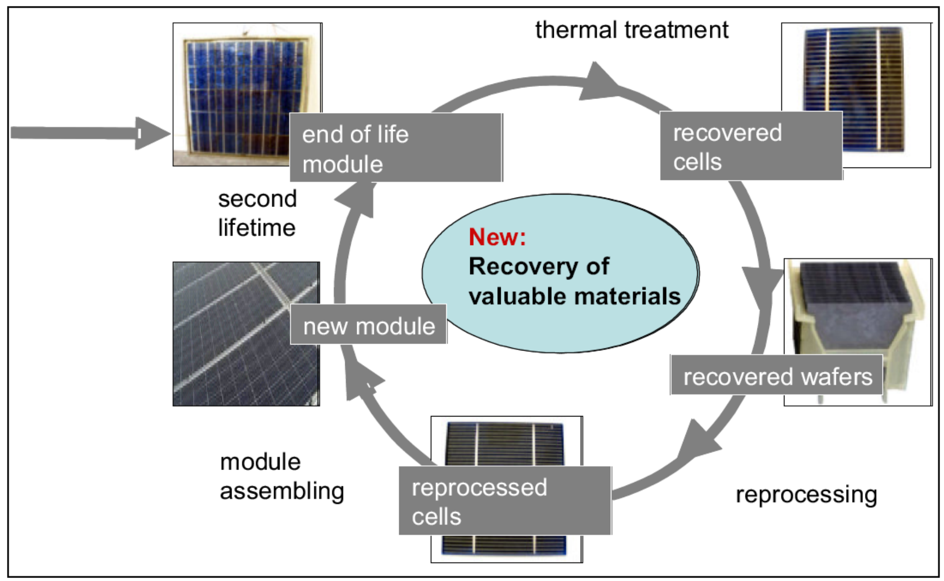


Fig. 4.56: Recycling through recovery of PV cells

4.4 SW based PV System Design

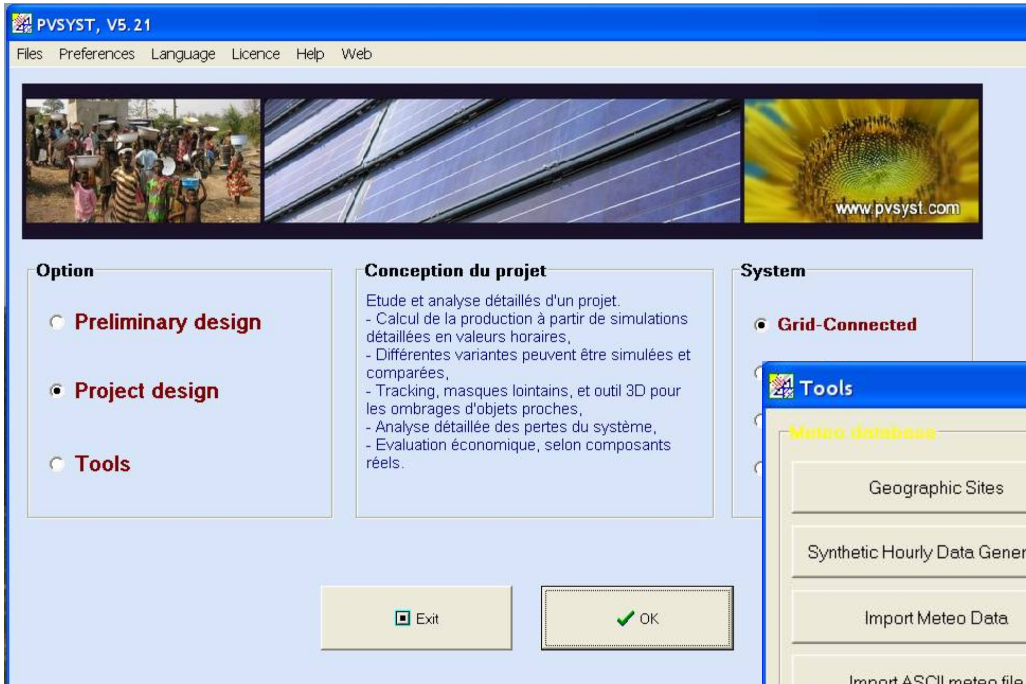
4.4.1 Introduction to the PVSYST SW

- PVSYST:
  - SW for the design and detailed analysis of PV systems :
    - Grid-independent, grid-connected, PV pumps, PV systems connected to DC grids (public transports)

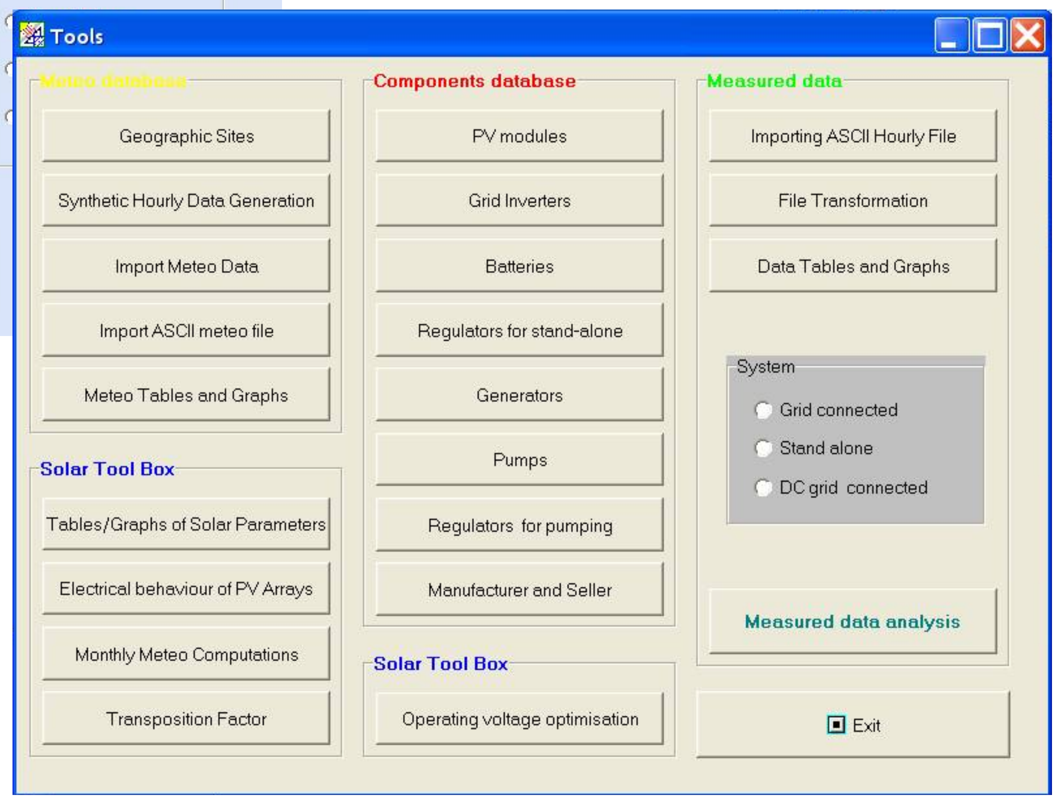
- Author :
  - Dr. André MERMOUD
  - University of Geneva, Groupe Energie (CUEPE)

- web : www.pvsyst.com

- Licences :
  - Free licence available for 30 days : download on website (after 30 days SW works in «limited» mode)
  - For full license, contact the CUEPE (www.unige.ch/cuepe), licence fees:
    - Full license (Preliminary design, Project design, Tools) 800 CHF
    - Full license for additional machines 200 CHF/machine
    - Full license for educational purpose -20%
    - Full license, update from the version 4.xx 100 CHF



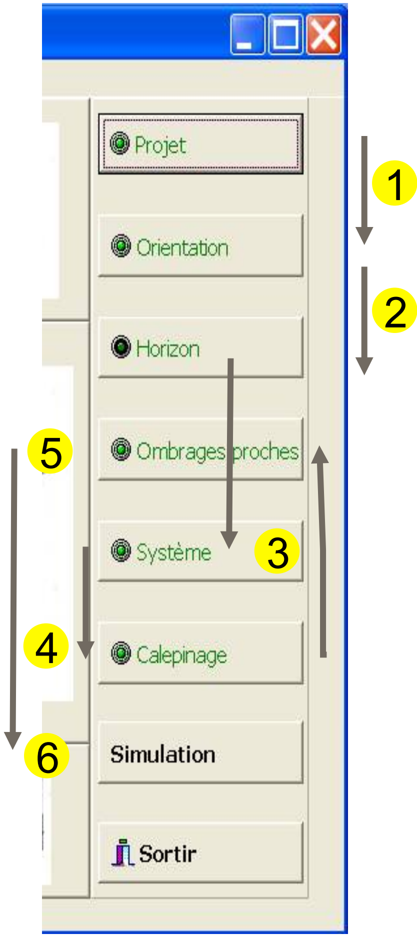
- The menus :
  - « Preliminary design », allows an approximate, but «quick», pre-design of a PV project
  - « Project design », complete and detailed project design



- The « Tools » menu is useful to:
  - Enter a new geographic site
  - Evaluate some design parameters (ex. inclination & spacing of sheds)
  - Consult the components data base (panels, inverters) and their characteristics

4.4.2 Main Functionalities, tips & hints

- Flow chart

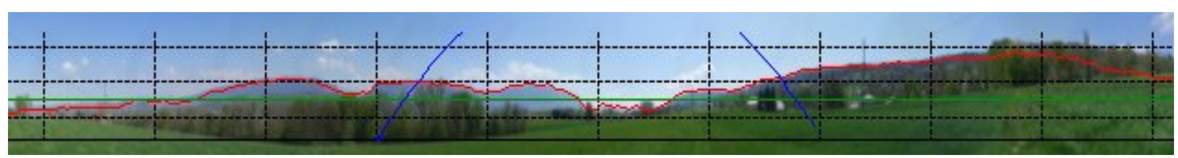


Some Advice:

- Use the  button or F1 – key to obtain additional information or help.
- Use explicit titles and filenames for the different projects and variants to be designed or analyzed.
- The orientation data needs to be re-used for the definition of the shading zones, take care to note the essential data:
- (inclination angle, azimut angle; PV surface)
- For a first approach, step over the «near shading» menu and introduce the PV system data
  - Number, orientation and size of the PV panels
  - Choose the «Sheds» menu if needed
  - Once the PV system is defined, enter in the «Shading» menu *(if needed)* where the previously defined data will be useful for the definition of the shadow effects
- Simulate, save the project definition and save the results (pdf file)

4.4.2.1 Geographic location data

- If the data base does not contain a pre-defined site close to the project site, it might be useful to enter a new geographic site:
  - Menu « tools » -> « geographic site »
  - Find the geographic coordinates of the site (GPS, or enter the name of the city or location on Wikipedia):
    - http://fr.wikipedia.org/wiki/Yverdon
  - Find the local Irradiation (G_{d0} in kWh/m²) and meteo data, (ex. for EU sites):
    - http://re.jrc.ec.europa.eu/pvgis/apps/radmonth.php?lang=en&map=europe
      - Choose « Solar Irradiation »
      - Activate the "Represent graphically the monthly data" case
      - Enter the Latitude and Longitude data
      - Convert (if necessary) the data units to the one used by PVSYST
    - For wind data, p.ex. http://www.wind-data.ch/messdaten/
    - For the horizon: http://www.sober-software.com/fr/produits/carnaval.html
    - Save the data entered!

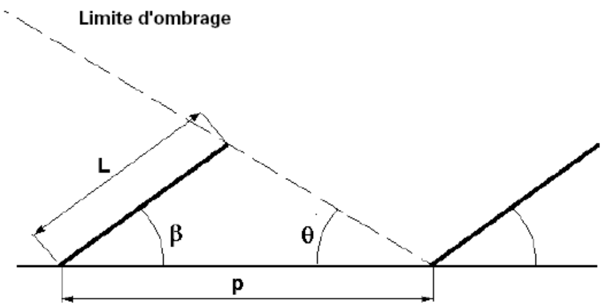


4.4.2.2 Inclination & Spacing of Sheds

The inclination angle and spacing of sheds (on flat rooftops) may be chosed according:

- The "ideal" inclination angle for Switzerland (approx. 30°to 45°) does not correspond to the optimal angle for the sheds, due to the mutual shading effects.
- A lower inclination angle (~15°) allows a better yield with a given available area
- The energy production is slightly lowered. The economic analysis needs to confirm that the loss of energy does not jeopardize excessively the energy production costs.
  - The lower the inclination, the slower will be the snow evacuation in winter. Nevertheless, due to the weak radiation energy in winter, the over-all loss due to snow effects is rather moderate.
    - Such additional losses may be entered in:
      - System -> array losses -> Soiling loss (activate «monthly values»)
  - Avoid the horizontal panel configuration. This in order to avoid excessive losses due to dirt deposits (see §4.1.6)
- Empiric formula[1] :
  - Limit θ to max. 18°

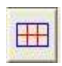
$$P = L \cdot \frac{\sin(180° - \beta - \theta)}{\sin \theta}$$

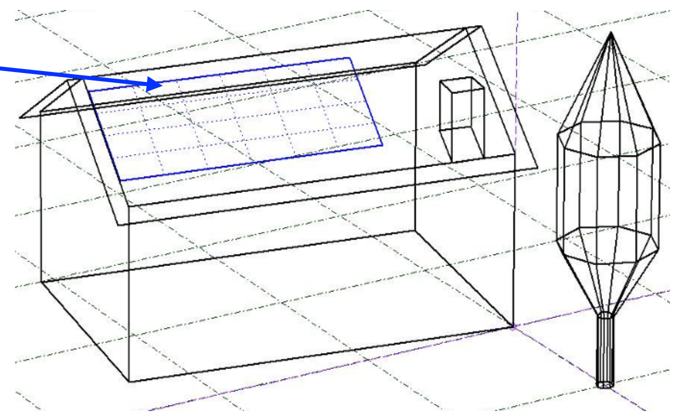


[1]Pacer 1996 : Centrales PV, guide pour le dimensionnement et la réalisation de projets

4.4.2.3 Shadow effects

Menu « near shading »:

- The PV panel orientation and configuration as well as the PV panel area has to be identical to the definitions used in the menus «orientation» and «system»
- Following options are available:
  - No shading: (no need to complete the rest!)
  - Linear shading: Area of shadow increase and decreases linearly. Useful for amorphous or thin film technologies
  - Module string shading: takes into account the shadow effect on the different cells of the module and on the modules of a PV string.
    - This option needs a partitioning of the «PV plane» using the partitioning functionality: 

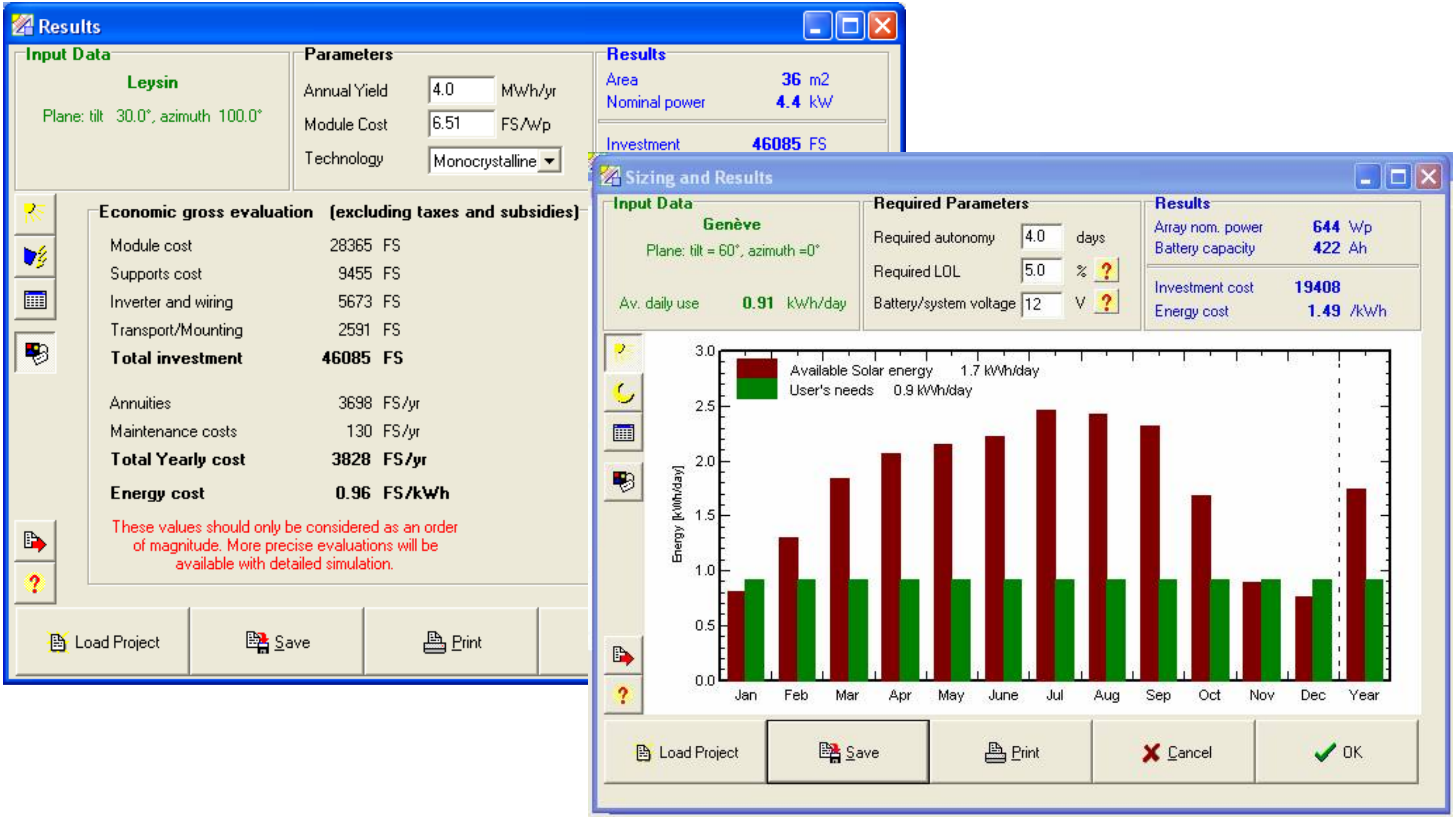


- During the orientation definition phase, represent first the entire scene within the axes disposition proposed. Re-orient the system, if necessary at the end of the definition phase.
  - It might be useful to save the disposition separately, to re-use it for other projects or variants.
- Finally PVSYST computes the correction coefficient tables, taking into account the shadow effects.

4.4.2.4 Error Messages

- A red error message indicates that a critical system configuration has been detected that prevents the program to undertake the needed calculations.
- An ***orange*** error message represents a warning, this might be ignored by the user
- As example, some errors concerning the inverter (choice) are listed hereafter:
  - *The Array MPP operating Voltage is lower than the Inverter Minimum Operating Voltage* : Increase the minimum inverter voltage (change the inverter type) or the number of modules of the PV string.
  - *The Inverter power is slightly oversized* : Due to this oversizing, the inverter may not operate at its optimal efficiency, specially for low irradiation conditions (low power).
  - *The Inverter power is strongly oversized* : Same condition than above, but it might jeopardize the energy cost of the system; it is strongly recommended to change the inverter type.
  - *The Inverter power is slightly undersized* : This warning might be totally acceptable for middle european countries. In fact, the maximum power may only occur under ideal irradiation conditions (STC), which will be rarely reached in reality and therefore cause a minimal loss of energy by the system.
  - *The Inverter power is strongly undersized* : This time the loss of energy might be unacceptable; it is strongly recommended to change the inverter type.
  - *The Array MPP operating Voltage is greater than the Inverter Minimum Operating Voltage* : It might be useful to reduce the number of modules in one string or to change the inverter type.

4.4.2.5 Calculation results example



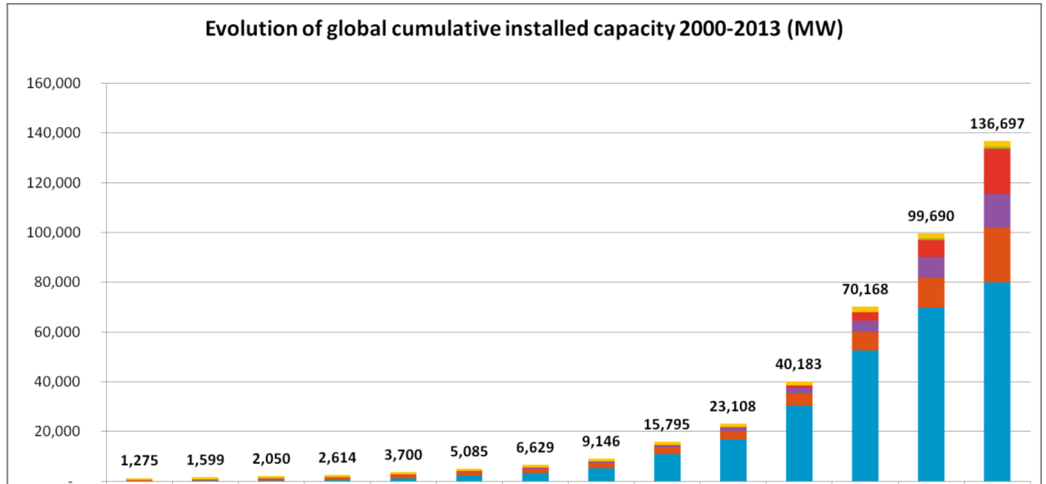
4.5 Future development & trends

4.5.1 PV market evolution

The installed PV peak power has shown a tremendous increase in the last decade (see Fig. 4.60). The **EU has become world leader in PV installed capacity**, followed by APAC (Asia&Pacific), China, USA.

The **EPIA** (European Photovoltaic Industry Association) does not only follows the market and PV price evolution, but is also active in promotion and forecast of PV industry and PV energy growth.

The PV development forecast are of course (as any forecast) strongly dependent on the applied hypothesis and scenarios. EPIA has foreseen **3 different scenarios** for the PV market and energy development:



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,590	2,098	2,098	2,183
MEA	-	-	-	-	1	1	1	2	3	25	80	205	570	953
China	19	24	42	52	62	70	80	100	140	300	800	3,300	6,800	18,100
AMERICA	21	24	54	102	163	246	355	522	828	1,328	2,410	4,590	8,365	13,518
APAC	368	496	686	916	1,198	1,502	1,827	2,098	2,628	3,373	4,951	7,513	12,159	21,992
Europe	116	249	381	580	1,283	2,264	3,258	5,274	10,970	16,777	30,352	52,462	69,699	79,952
TOTAL	1,275	1,599	2,050	2,614	3,700	5,085	6,629	9,146	15,795	23,108	40,183	70,168	99,690	136,697

Fig. 4.60: PV Installed peak power in MWp 2000-2013

- **Reference** scenario: assuming a power consumption (+2.4%/year) and industry growth in accordance to the IEA (International Energy Agency).
- **Accelerated** growth scenario: Assuming the PV industry will be continuously supported by governmental incentives as they are today.
- **Paradigm** scenario: assuming the PV industry to be used at its max. economic and technic capabilities.

As expected (fig. 4.61) the annual and cumulated growth depend strongly on the assumed scenario. The annual growth from 2010 to 2050 vary from a factor of 2 to a factor of 25.

According EPIA studies "12% market share for PV is a demanding but achievable and desirable objective for 2020". Moreover EPIA estimates that "In average 30 full-time equivalent (FTE) jobs are created for every MWp installed PV power."

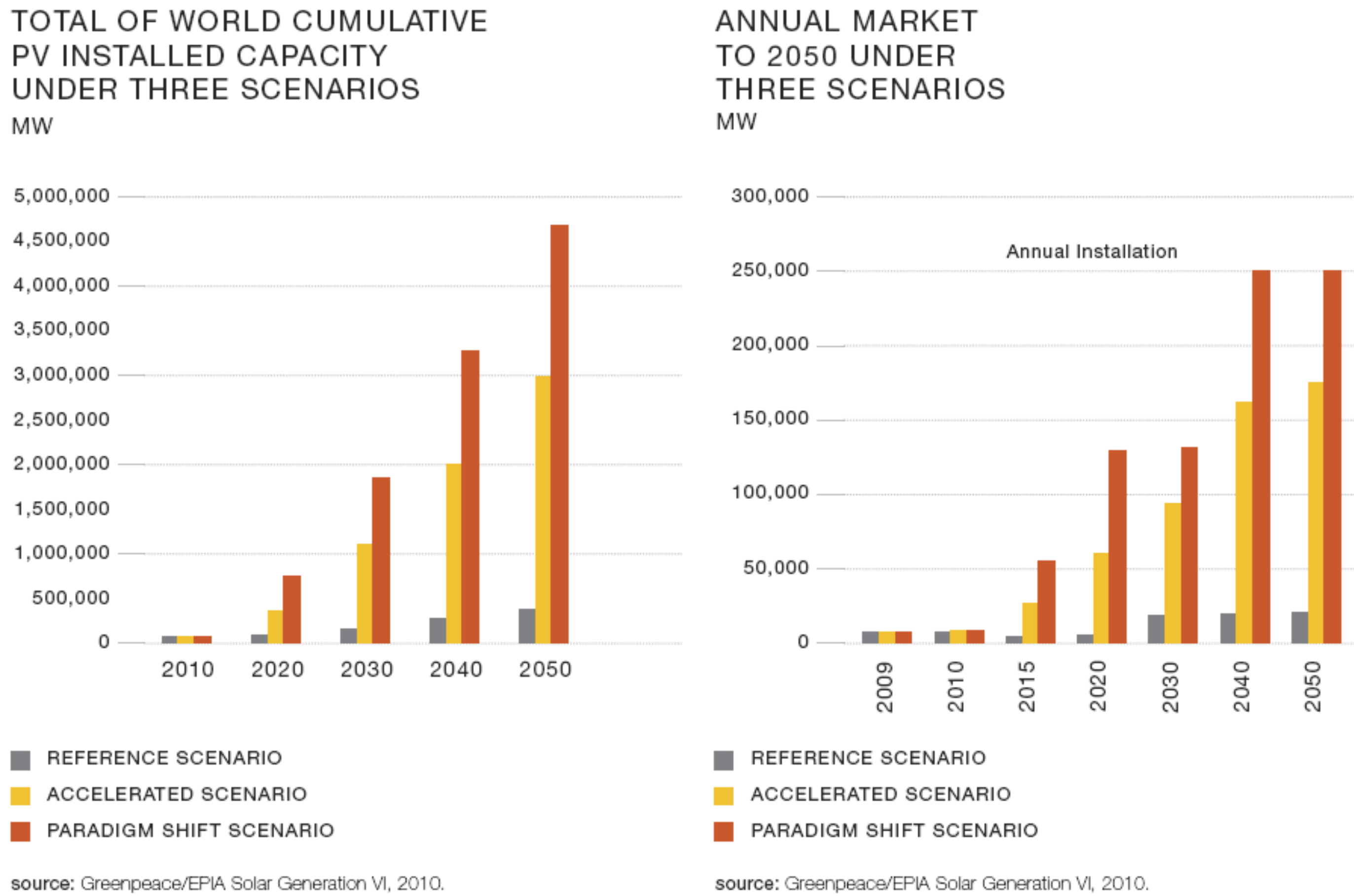


Fig. 4.61: PV Installed peak power forecast 2010-2050, under 3 different scenarios

As the economic and power consumption growth vary "regionally" over the world, the expected PV installed capacity also does. Table 4.5 shows the "regional dispatching" for 2020 and 2030.

WORLD-WIDE CUMULATIVE PV INSTALLED CAPACITY AND PRODUCTION TO 2050 USING THE REFERENCE, ACCELERATED AND PARADIGM SHIFT SCENARIOS

		2007	2008	2009	2010	2015	2020	2030	2040	2050
Reference	MW	3	15,707	22,999	30,261	52,114	76,852	155,849	268,893	377,263
	TWh	0	17	24	32	55	94	205	377	562
Accelerated	MW	3	15,707	22,999	34,986	125,802	345,232	1,081,147	2,013,434	2,988,095
	TWh	0	17	24	37	132	423	1,421	2,822	4,450
Paradigm	MW	3	15,707	22,999	36,629	179,442	737,173	1,844,937	3,255,905	4,669,100
	TWh	0	8	24	39	189	904	2,266	4,337	6,747

source: Greenpeace/EPIA Solar Generation VI, 2010.

Table. 4.4: PV Installed peak power forecast 2010-2050, for 3 scenarios

PV INSTALLED CAPACITY EVOLUTION BY REGION
GW

Reference Scenario	OECD Europe	Transition Economies	OECD North America	Latin America	Developing Asia	India	China	Middle East	Africa	OECD Pacific	Total
2020	30	0	16	1	2	1	8	1	4	13	**77**
2030	38	0	37	3	11	4	25	4	15	19	**156**
Accelerated Scenario											
2020	140	1	77	9	19	20	29	3	16	31	**345**
2030	280	20	285	47	70	71	150	30	62	64	**1,081**
Paradigm Shift Scenario											
2020	366	3	145	15	24	33	38	11	21	33	**688**
2030	631	42	460	66	83	113	242	47	85	77	**1,845**

source: Greenpeace/EPIA Solar Generation VI, 2010.

Table. 4.5: PV Installed peak power forecast 2010-2050, with world-wide dispatching

4.5.2 PV energy cost evolution

As expected PV market growth will also induce a continuous decrease in the installation and therefore on the energy costs of PV energy.

EVOLUTION OF PRICES
OF LARGE PV SYSTEMS
€/KWp

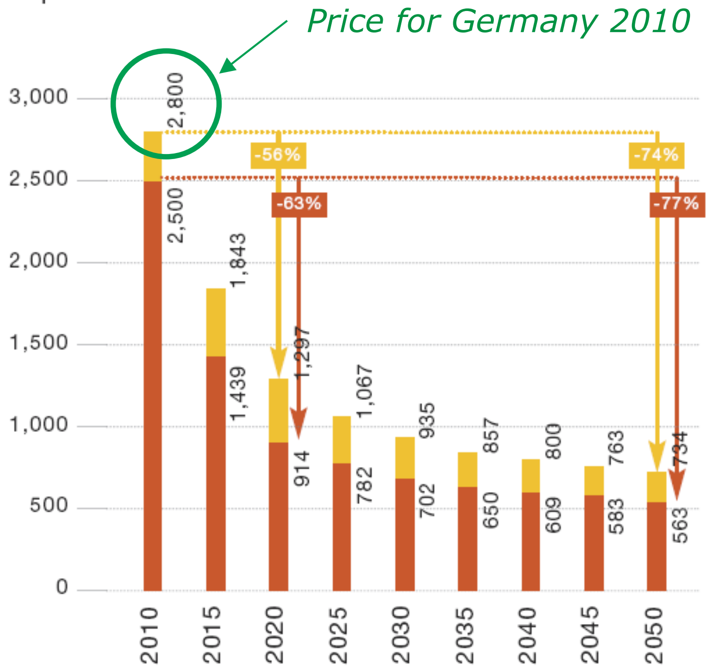


Fig. 4.63

ACCELERATED SCENARIO
PARADIGM SHIFT SCENARIO

source: Greenpeace/EPIA Solar generation VI 2010.

DEVELOPMENT OF
UTILITY PRICES AND PV
GENERATION COSTS
€/KWh

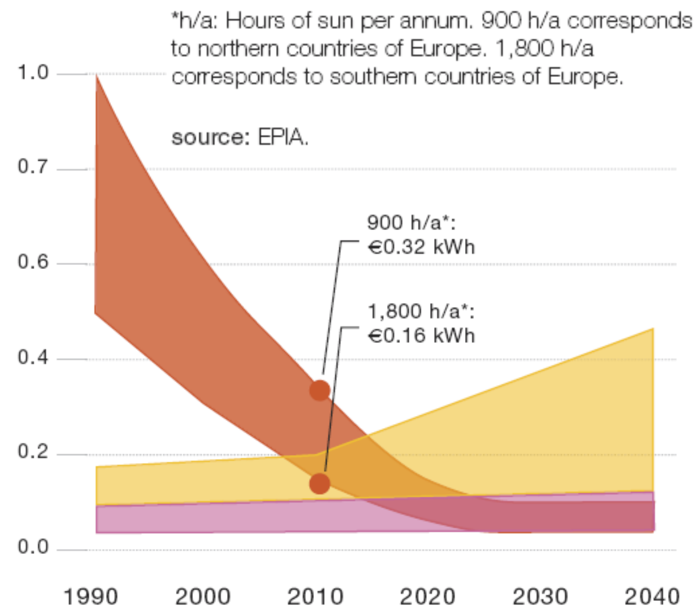


Fig. 4.64

PV GENERATION COST AT LOWEST PRICE
UTILITY PEAK POWER
UTILITY BULK POWER

The Table 4.6 hereafter shows the roadmap of the EPIA for the cost objectives to be reached, with the corresponding expected energy efficiencies of the different PV technologies.

PV TECHNOLOGY – 10-YEAR OBJECTIVES

Table. 4.5

Solar Europe Industry Initiative: PV technology roadmap for commercial technologies		2007	2010	2015	2020
Turnkey price large systems (€/Wp)*		5	2.5-3.5	2	1.5
PV electricity generation cost in Southern EU (€/kWh)**		0.30-0.60	0.14-0.20	0.10-0.17	0.07-0.12
Typical PV module efficiency range (%)	Crystalline silicon	13-18%	15-19%	16-21%	18-23%
	Thin Films	5-11%	6-12%	8-14%	10-16%
	Concentrators	20%	20-25%	25-30%	30-35%
Inverter lifetime (years)		10	15	20	>25
Module lifetime (years)		20-25	25-30	30-35	35-40
Energy payback time (years)		2-3	1-2	1	0.5
Cost of PV + small-scale storage (€/kWh) in Southern EU (grid-connected)***		-	0.35	0.22	<0.15

note: Numbers and ranges are indicative because of the spread in technologies, system types and policy frameworks.
* The price of the system does not only depend on the technology improvement but also on the maturity of the market (which implies industry infrastructure as well as administrative costs).
** LCOE varies with financing cost and location. Southern EU locations considered here range from 1,500 (e.g. Toulouse) to 2,000 kWh/m² per year (e.g. Siracusa).
*** Estimated figures based on EUROBAT roadmaps.

source: Solar Europe Industry Initiative Implementation Plan 2010-2012, Strategic Research Agenda.

PV technology may be also used in conjunction with other renewable energies. Hereafter a cost comparison for a small grid-independent energy powering system, based on PV and wind energy.

The example shows, that the relative high investment costs of renewable energies may be compensated by the low maintenance & running costs.

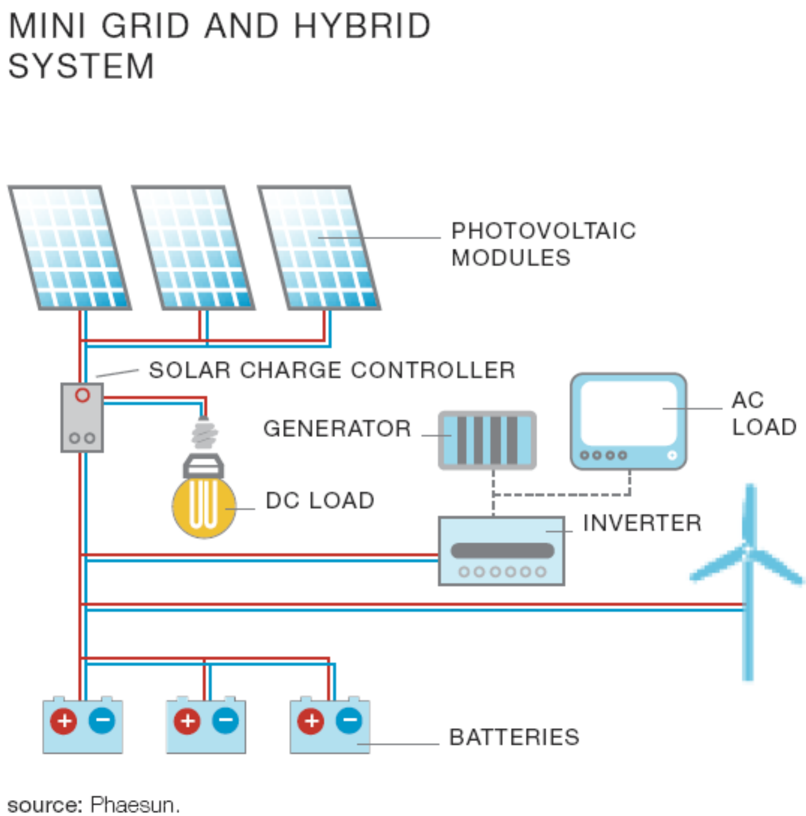


Fig. 4.65

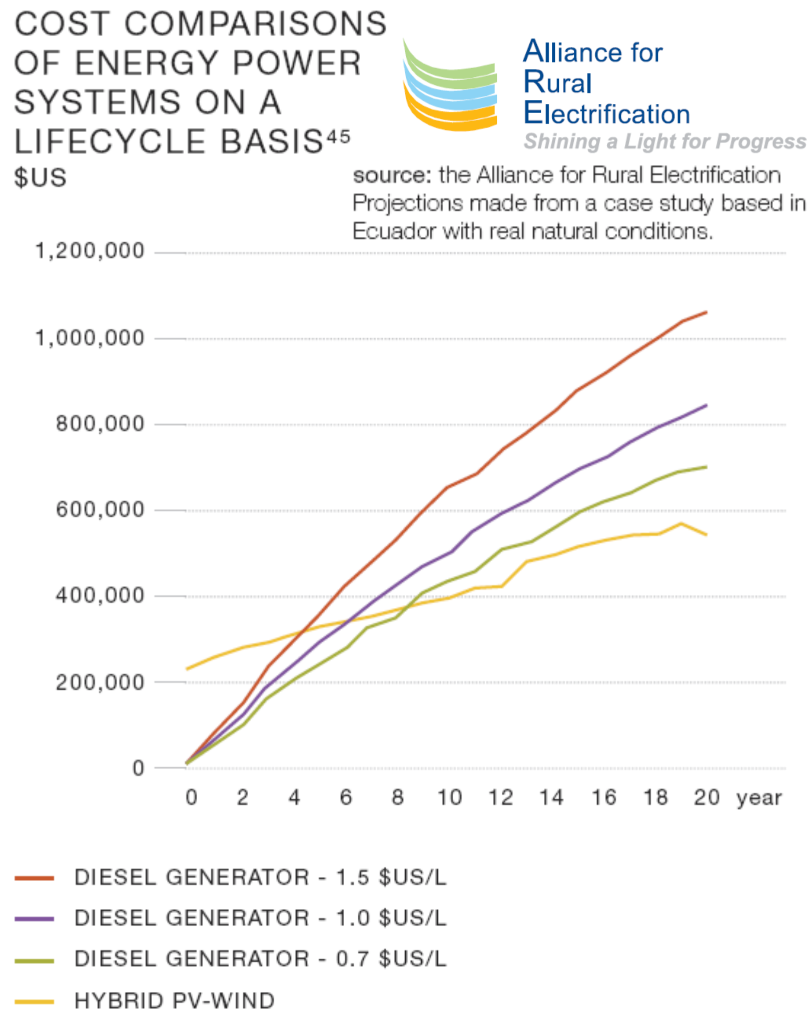


Fig. 4.66

4.5.3 PV Market & PV industry in Switzerland

PV capacity in Switzerland reached 757 MWp by the end of 2013. The installed capacity in 2013 exceeds the cumulated PV installed power from 1987 to 2011.
In Switzerland, the majority of PV Installations are grid-connected plants, built mostly on the roofs of buildings. Larger installations (> 100 kW) are usually flat-roof mounted on commercial buildings, offices etc. A new market developed in 2009 with tilted roof installations on farmhouses with sizes ranging from 30 up to more than 100 kW.
The size of residential systems increased from a de facto standard in earlier years of 3 kW to up to 15 kW. The trend goes towards using the whole roof facing South (SE to SW) and not only a part of it. This is due to the fact that the Swiss FiT has no upper limits concerning the size of the installation.

A few larger PV plants (> 1MWp) exist also : Migros Neuendorf (5.2 MWp), Palexpo Genève (4.2 MWp), EPFL (2.0 MWp), Stade de Suisse in Bern (up to 1.3 MWp).

The value of PV installed systems in 2012 is estimated at 650 mio CHF.

For 2014 to 2017 an annual growth of 300 MWp to 400 MWp is expected, financed with the existing FiT scheme.

The PV part on the total electric energy production represents end of 2013, 0.9% (or 544 MWh), whereas compared to the total installed peak power the PV part represents 3.8% of the total electric power production.

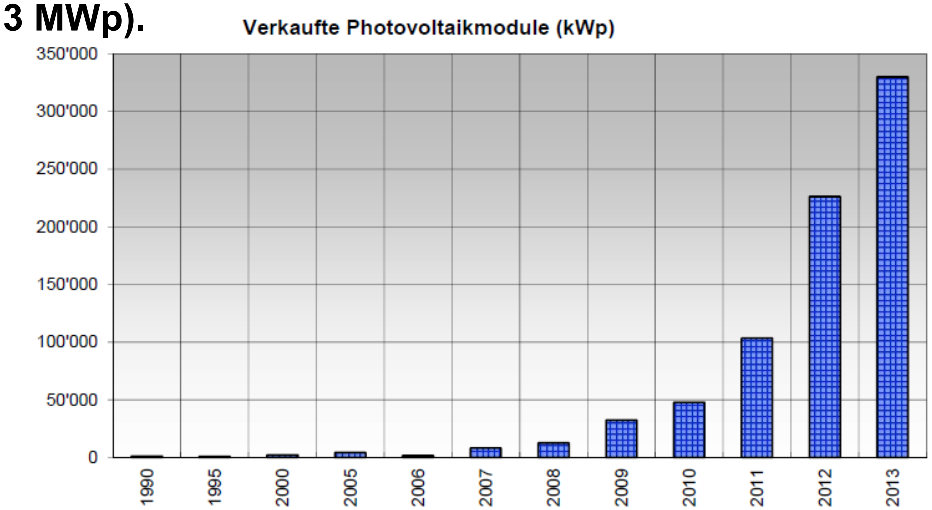


Fig. 4.70: Yearly installed PV peak power in Switzerland

The PV industry can be subdivided into 2 different domains:

- **PV production : industry active in the Silicon wafer and PV module production, mainly for BIPV (Building Integrated PV) applications. The main companies are: Sunage(TI), 3S Photovoltaics part of Meyer Burger, SES Solar (GE), Swisswafer (TG). Pramac (Ti) and VHF Technologies (Flexcell) PV module production plants shut down in 2012.**
- **PV components : industry active in the production of BOS (Balance of Systems) components (such as inverters, connexion boxes and cables) and PV manufacturing equipment. Main companies are: Oerlikon Solar (sold to Tokyo Electron end of 2012), Applied Materials, Sputnik (inverters), Studer Electronics, Multi Contact and Huber & Suhner.**

Along with these industrial activities, the R&D as well as the installation project, integration and maintenance service activities represent also an important job generating PV activity.

The total turn-over of the swiss PV industry is estimated at 1200 mio CHF in 2012 (750 mio CHF for PV production, 450 mio CHF for BOS,PV components industry and for services).

The swiss PV activities represent in total about 8’600 FTE jobs (for 2012).

Fig. 4.71: PV panel production (Pramac until spring 2012)

■ 2008 Biogas Plant in Porrentruy

- Installed power 48 kWp
- 780 m^2 Si thin-film PV panels
- yearly energy production 43.2 MWh
- Investment cost of 0.44 Mio CHF
- pay-off time of 25 years (supposed)
- -> Energy cost at 0.68 CHF per kWh

■ 2011 «Palexpo» in Geneva

- Installed power 4.2 MWp
- 30000 m^2 poly-crystaline PV panels
- yearly energy production 4’200 MWh
- Investment cost of 15 Mio CHF
- pay-off time of 20 years
- Energy cost at 0.30 CHF per kWh*

**including 0.05 CHF/kWh tax*

- **2012 Residential house in Rupperswil (AG)**
  - **Installed power 20 kWp**
  - **102 m^2 mono-crystaline PV panels**
  - **yearly energy production 20'400 kWh**
  - **covers 100% of electricity (7600 kWh/y) & e-mobility (60'000 km/y) needs**

- **2013 "Migros" Distribution Center in Neuendorf (SO)**
  - **Installed power 5.2 MWp**
  - **32000 m^2 mono-crystaline PV panels**
  - **yearly energy production 4.84 GWh**
  - **Investment cost of 13.3 Mio CHF**
  - **pay-off time of 20 years (supposed)**
  - **-> Energy cost at ~0.2 CHF per kWh**

4.6 Exercises

Exercise 1

Consider the geographic location of Lausanne (latitude φ=46.53°) and the direct and indirect radiation expressions given in §4.1.2 and §4.1.3.

a) Estimate the direct daily extraterrestrial irradiation $B_{0d}(0)$ of Lausanne for the 1. August.

b) Estimate the clear sky factors K_{Tm} of Lausanne for the 13th of December and the 10th of June. Estimate the corresponding diffusion fraction coefficients F_{Dm} and compute the diffused, direct and reflected mean energy for a PV panel titled by an angle of 30° and a reflection coefficient of 0.08 (lake).

Exercise 2

Consider the monthly mean collected solar energy $G_{dm}(0)$ for Lausanne (Table 4.1).

a) Estimate the mean value and standard deviation for the winter (october to march) and summer (april to september) months.

b) Estimate the radiation interval for a 68%, 90% and 95% confidence level. Compare the collected energy during winter and summer months.

Exercise 3

Estimate the MPP power (P_{MPP}), the I_{SC} and V_{OC} values as well as the system performance ratio PR for a PV system based on BP-585 type solar modules and assuming:

a) Month of December : T_a = 5°C; G_{eff} = 300W/m^2, η_{inv} = 0.9, 2% cabling losses.

b) Month of June : T_a = 25°C; G_{eff} = 900W/m^2, η_{inv} = 0.95, 2% cabling losses.

Exercise 4

Design a small PV AC Household system assuming:

- **A yearly energy production request of 2000 kWh**
- **A mean performance rate of 75%**
- **A mean daily irradiation of 3.5 kWh/m^2**
- **A ambient temperature varying from -10°C to +35°C**

Calculate (estimation)

a) The total needed PV area (based on BP-585 modules; Area BP-585 = 0.65m^2)

b) The P_{MPP} value of the system.

c) The min. and max voltage and current values for the inverter

d) The mean monthly availability a_m based on the G_{0d} values for Lausanne (Table 4.1)

e) Estimate the energy cost rate (SFr/kWh), the economic yield and the ROI of the installation.

Exercise 5

Design a PV AC system for a shopping center in Geneva assuming:

- **A total available area (flat roof) of 100 m^2**
- **The owner requires a maximized yield and ROI**

Calculate and use the PVSYST to optimize (detailed analysis)

a) Verify different PV panel spacing and inclination angles (between 5° and 50°)

b) Analyze different PV panel types (mono - crystalline, thin-film,…).

c) Compute for each variant the annual yield and ROI

d) Analyze the effect of near and "far" shadows (horizon).

4.7 Literature

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[9] ***"PACER Installation Photovoltaïques Autonomes",*** *Swissolar Colombier, N° Cmd 724.428F,* *DDC Office Fédéral des questions conjoncturelles*

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4.8 Annexes

4.8.1 Irradiation $G_{dm}(0)$ Statistics for Switzerland

	Lat. °N	Long. °E	Alt. m		Jan	Fév.	Mars	Avril	Mai	Juin	Juil.	Août	Sept	Oct.	Nov.	Déc.	Année kWh/jr	Année kWh/an
Bâle	47.6	7.6	316	Gh	0.97	1.61	2.55	3.57	4.61	5.17	5.58	4.74	3.37	2.00	1.10	0.81	3.01	1097
				Te	1.2	1.7	6.1	9.1	13.3	16.3	19.6	19.1	15.3	10.8	5.1	2.6	10.0	°C
Berne	46.9	7.4	540	Gh	1.06	1.75	2.81	3.73	4.68	5.20	5.68	4.84	3.53	2.06	1.13	0.84	3.11	1135
				Te	-0.5	0.2	4.5	7.7	12.1	15.1	18.6	18	14.3	9.5	3.7	0.8	8.7	°C
Coire - Ems	46.8	9.5	600	Gh	1.42	2.18	3.26	4.37	5.10	5.33	5.68	4.77	3.70	2.52	1.47	1.10	3.41	1244
				Te	-0.2	0.7	5.2	8.5	12.9	15.3	18.7	18	14.5	10.4	4.3	1.1	9.1	°C
Davos	46.8	9.9	1590	Gh	1.68	2.64	4.03	5.03	5.61	5.70	5.87	5.00	3.97	2.77	1.73	1.35	3.78	1381
				Te	-4.9	-5	-1.6	1.5	6.1	8.9	12.5	11.8	8.9	5.3	-0.5	-3.4	3.3	°C
Genève	46.3	6.1	420	Gh	0.94	1.64	2.97	4.07	5.03	5.73	6.10	5.19	3.87	2.23	1.03	0.77	3.30	1204
				Te	1	1.8	5.6	8.8	13.2	16.6	20.3	19.6	15.9	11	5.3	2.6	10.1	°C
La Chaux-de-Fonds	47.1	6.8	1020	Gh	1.32	2.07	3.06	3.87	4.39	5.00	5.61	4.74	3.53	2.29	1.40	1.10	3.20	1168
				Te	-2	-1.5	1.3	4.4	8.7	11.7	15.4	14.7	11.6	7.8	2.4	0	6.2	°C
La Frétaz	46.8	6.6	1200	Gh	1.32	2.04	3.00	3.77	4.45	5.00	5.58	4.74	3.53	2.19	1.37	1.10	3.17	1159
				Te	-1.5	-1.7	1	3.5	7.9	10.7	14.6	14.2	11.1	7.3	2.3	0.5	5.8	°C
Locarno-Monti	46.2	8.8	366	Gh	1.45	2.11	3.32	3.97	4.77	5.67	6.03	5.26	3.83	2.29	1.50	1.19	3.45	1259
				Te	3.1	4.1	8.2	10.8	14.8	18.1	22	21.2	17.5	12.5	7	4.4	12.0	°C
Lausanne-Pully	46.5	6.7	460	Gh	1.03	1.71	2.94	4.00	5.06	5.60	6.06	5.10	3.77	2.23	1.13	0.87	3.29	1202
				Te	1.7	2.2	5.9	8.9	13.3	16.5	20.3	19.7	16.1	11.5	5.9	3.2	10.4	°C
Lugano	46.0	9.0	273	Gh	1.26	1.89	2.84	3.37	4.19	5.03	5.39	4.97	3.67	2.13	1.40	1.06	3.10	1131
				Te	3	4.1	8	10.8	14.9	18.4	22.3	21.4	17.7	12.9	7.4	4.3	12.1	°C
Neuchâtel	47.0	6.6	485	Gh	0.84	1.57	2.77	3.83	4.81	5.30	5.84	4.94	3.57	2.00	0.93	0.68	3.09	1128
				Te	1	1.5	5.5	8.8	13.3	16.3	20.2	19.6	15.8	10.9	5.2	2.4	10.0	°C
Sion	46.2	7.3	480	Gh	1.39	2.18	3.32	4.63	5.58	5.93	6.35	5.39	4.03	2.68	1.47	1.13	3.67	1341
				Te	-0.8	1	6	9.6	13.9	16.7	20	19	15.2	10.1	3.8	0.1	9.6	°C
Saint-Gall	47.4	9.4	780	Gh	1.06	1.79	2.77	3.77	4.68	4.93	5.39	4.58	3.23	2.00	1.10	0.87	3.01	1100
				Te	-0.6	-0.5	3.5	6.5	11	13.6	17.2	16.7	13.4	9.1	3.4	1	7.9	°C
Zurich-Kloten	47.5	8.5	436	Gh	0.90	1.68	2.68	3.77	4.77	5.20	5.58	4.71	3.40	1.94	0.93	0.68	3.02	1102
				Te	0	0.3	4.8	8.2	12.8	15.7	19	18.3	14.6	9.8	4	1.4	9.1	°C

Table 4.10: Irradiation statistics for different Swiss locations (source [9])

4.8.2 Force and mechanical resistance calculation

In Switzerland the SIA (society for architects and civil engineers) is giving 2 guidelines for the efforts on roofs (applicable also for roof mounted systems):

- **Snow pressure (table 4.11): is given as a function of the altitude above sea level (h). The minimal snow pressure to withstand is defined at 90 kg/m². For roofs with inclination angles α > 60°, the pressure c an be downsized to p' = p·cosα.**
- **Wind pressure (table 4.12): is given as a function of the height above ground. For tilted panels mounted on flat roofs, the effects on head- and down-wind have to be considered separately.**

h m	p kg/m²	h m	p kg/m²	h m	p kg/m²	h m	p kg/m²	h m	p kg/m²
400	92	500	123	600	159	700	202	800	251
900	308	1000	371	1100	440	1200	516	1300	599
1400	688	1500	784	1600	886	1700	995	1800	1111
1900	1233	2000	1362						

Table 4.11: Snow pressure vs. altitude according SIA 160 standard

Hauteur au-dessus du sol	m	0-5	5-15	15-40
Force du vent q	kg/m²	70	85	100

Table 4.12: wind pressure vs. height according SIA 160 standard

For the reaction forces applied on a inclined support system (for flat roof mounting), following formulas may applied:

- **Head-wind**: $K = c \cdot q \cdot A$

$$K_x = K \cdot \sin\alpha \qquad R_x = K_x$$

$$K_y = K \cdot \cos\alpha \qquad R_y = K_y + G$$

with: **c : security factor (1 to 1.5)**

q : total pressure applied

A : panel Area

- **Down-wind**: $R_y = G - K_y$

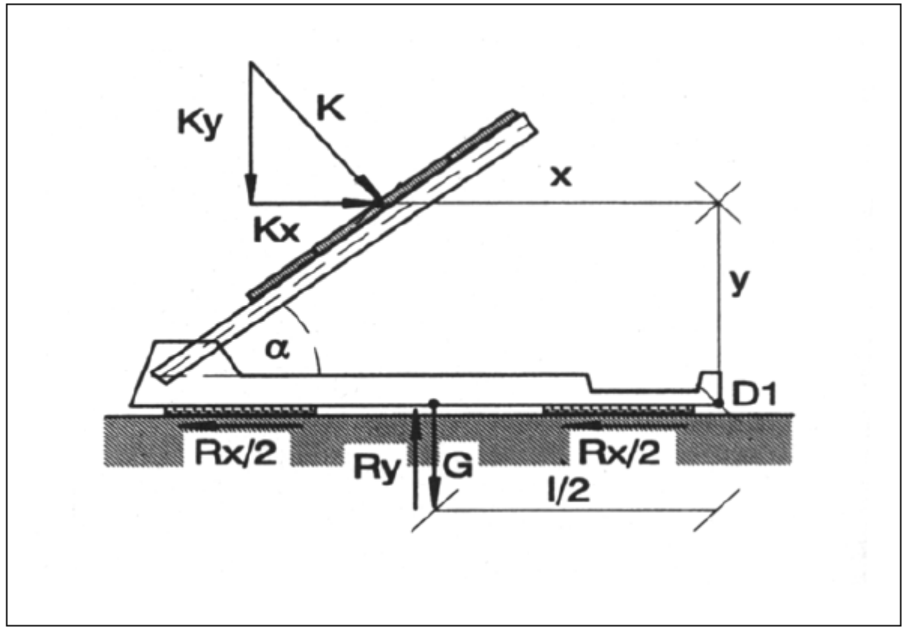

Fig. 4.80: reaction forces in inclined support system

In addition to the reaction forces, the reaction torques (sum of force moments to be applied is zero) may also be evaluated for this panel support system.

For systems installed on a inclined roof, the reaction forces are directly estimated with the estimation of K_x and K_y.