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Photovoltaic electric energy from laboratory to ended plant. A first look on the results collected after the first Friuli Venezia Giulia public announcements

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Abstract. Photovoltaic technology is one of the best nowadays to produce electric energy from renewable sources. The research of more efficient energy conversion photovoltaic cells and of development programs in advanced countries are starting to show the first results. Referring to this, new materials and physic laws are considered to improve efficiency conversion, and in engineering more efficient plants are being planned. At the moment also in our Region we are overcoming experimental steps, carrying out conventional plants with reliable technological realizations on roof buildings, in houses and hangars, also thanks to public announcements. In Italy, indeed, a special law called "10000 photovoltaic roofs" promotes photovoltaics technology realizations with financial incentives on private and public buildings being offered by Enviroment Ministery and Regions. Friuli Venezia Giulia Region has been assigned economics shares to private citizens and Public Istitutions with public boards in 2001, 2003 and in 2005. In few years a market niche will grow and new professional workers will be employed in planning, installing and data collection and this will allow better provisional data production and consequently a more accurate evaluation to calculate economic gain. To perform this goal it is necessary to produce an afford from all the actors on the scene: schools, universities, credit banks, local bodies, all with available means and methods. Our group, self-named "Agathos", aims to improve Scientific and Technological Education (S&TE) and is building prototypes, with the help from school technicians and students, in an action-research approach to know and operate with renewable electric energy production system, in particularly based on photovoltaic effect. Our team has achieved links with research units, universities, schools and firms, and some components furnished assistance to local bodies and specialized photovoltaics plants installers. Our intention is to put the School in a network to produce didactical services to improve tech-

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nology and scientific education. Here we will consider the first results and difficulties that we must overcome, both in scientific and in technological aspects, if we wish photovoltaic technologies to spread in the territory in favour of environment, health and to save money.

Key words. Solids electric properties, photovoltaic effect, P-N junction, PV cell, S&TE prototypes**,** PV plant grid connected (GC) and stand alone (SA), electrons, holes, nominal power, efficiency, public announcements, save money.

Introduction. Photovoltaic technology utilizes the so named photovoltaic effect. A highly efficient apparatus to produce electric energy from photovoltaic source (*PV* in short terms) is the result of a long work of scientists and technologist. In consideration of names and dates that historians fixed to explain changes in paradigm (consider Kuhn) or, in a more general way – the acceleration in the knowledge field and technological innovations – we have chosen the most famous names in the spreading of scientific ideas.

The "starting point" in energy electric research from the matter has a name and date: Alessandro Volta, 1799. The scientist, born in Como, in a letter dated 20 March 1800 sent to Sir Joseph Banks, President of the Royal Society in London, announced to have built an "artificial apparatus"[1]. In the letter, written in French but published in English, there is the explanation of the famous electric battery that looks like the "organe électrique naturel" of Torpedo and Gimnoto. The revolutionary instrument performance was to convey a steady electric current without need to charge and charge to produce its effects. The shape of this apparatus inspired him the name of "appareil à colonne". From this term the modern term "electric battery" derives. A prototype of it was built in ITI "A. Malignani" laboratories in the occasion of bicentenary of Volta's discovery, 1799 (see photo 0.1).

In 1839 a French physicist Edmund Becquerel[2] discovered, casually, a photoelectric effect. This phenomenon appears on light beating against one of the two electrodes in an electrolytic solution of an electric cell. Bequerel's discovery was not profitable for technological development and nobody was able to explain such a mysterious phenomenon. Things began to change when crystalline selenium electric properties were discovered. First experiments were made by W. Smith, an American electrician, in 1873. He was a project head in the enterprise to install a transatlantic telegraph cable in 1867 when casually discovered that (it's the second time that a "chance" burst into the field of scientific discovery about the same phenomenon) the selenium, utilized to build a measurement apparatus, worked well during the day but not at all at night. The ex-

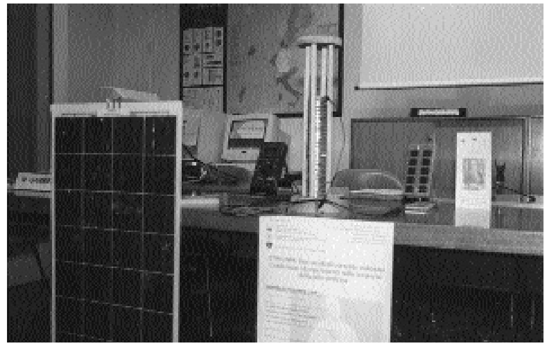


Photo 0.1. "*Dalla pila di Volta alla cella fotovoltaica*" Conference at meeting room of ITI "A. Malignani" in Udine, last conference with experiments of the Seminar: "(1799-1999) *Due secoli di corrente continua – Conferenze e esperimenti sulla scoperta della pila elettrica*", organized by AIF – Udine.

periences with selenium were carried on by two English scientists: G. Adams e R.E. Day. The first PV module was built by the newyorker C. Fritts. He had a brilliant idea to compose a wafer with selenium inside a metal plate and a semitransparent gold thin plate. Results were enthusiastic and the invention was considered a promising electric source from the sun. But nobody knew why the phenomenon was produced. Moreover, it's difficult to recognize a link from this phenomenon and Volta effect. A genius man had to show a new way, never thought before, Einstein. He was the man that solar electricians were waiting. In his paper published in 1905, Einstein considered the light composed of energy quantum particles, able to move electric charge units[3].

At this point physics laws and discoveries were made. It was the time to gather things.

Selenium was not a good technological solution because of low efficiency (only 1% of the radiant energy was transformed into electric energy). It was after transistor discovery in 1948 (J. Bardeen, W. Shokley e W. Brattain) that technologists worked on a solid technological basis: the "diode"[4]. The first PV diode o PV cell was composed by C. Fuller e G. Pearson in Bell Laboratory in 1954. Nowadays, technological progress is experimenting PV cells that have a very high efficiency near the physics limit.

Knowing PV plant generator as a scientific object, and the characteristics of its employment, means to utilize two electric current conduction models of explanation: the semi classical model and the quantistic model: the former for metal conductivity (copper, silver, aluminium, etc.), the latter for semiconductors (Si crystals in amorphous, polycrystalline or monocrystalline state).

In this paper we don't mention other substances of increasing interest to produce electric energy from the light, as film solar cell or biologics cells, above all for their too low efficiency.

The aim of our research is, considering the didactic interest, technology development and engineering applications, to promote students scientific and technological interest – in particularly to PV phenomena – with active learning methods applying knowledge of essential semiconductor conductivity properties to evaluate energy electric production from real PV plants, to find critical parameters that influence PV production and permit technical solutions for better investments.

For this, before showing plants schemes to students in the school, where a "brainstorming" was produced on occasion of the bicentenary of Volta's electric battery discovery, prototypes and a measurements apparatus were built to make the assembling and the discussion easy. With this choice PV physics generator theory was only one of the levels proposed to the students because the other was to put the "hands on" prototypes and to make measurements "indoor" and "outdoor" in open spaces.

If the reader's interest is mainly PV plants, then he can shift the first, second and fourth paragraphs to consider the others where the modules characteristics are dealt, and where are considered different ended and tested PV plants built with 26 February 2001 Friuli Venezia Giulia region financing.

Synthetic topics knowledge about materials electric conductibility physics, didactical experiences, project elements, elaboration of collected data and technical and economical aspects are divided into paragraphs as follows:

Conductivity electric topics are considered in paragraphs: 1. *Elements about electric properties of solids* and 2. *Conductivity in semiconductors*. In these paragraphs the theory of electric metals conductivity, from which derive Ohm's law and the other forms of it, is not developed. The main law of an electric circuit is a subject widely considered in a lot of electromagnetism, electrotechnics and electronics school books. But to evaluate engineering aspects it's necessary to consider essential physics behaviour as electric conductivity in metals which are the basis to understand insulators and semiconductors conductivity. The demanding readers are advised to refer to the bibliography to go deeper into these studies and researches.

In paragraph 3. *How PV module works* are still considered some elements of electric conductivity in semiconductors, but more closely joined to PV module electric energy production.

The paragraph 4. *"Agathos" project: experiences for an interactive science and technology didactics* is a "paper of memory", a "memoir" about a didactical work at school and it integrates, first of all, topics of paragraph number 3.

The paragraph 5. *PV plants. Technical schemes and considerations* has a popular spreading character. There are a lot of "web internet sites" that show typical PV electric plants with different interesting details. At the end of the paragraph are considered some elements of PV costs that are not present in popular technical literature.

In paragraph 6. *Some PV plants realized in the Region with public contributions*. First Public announcement 2001 are publicized some of the first typical PV plants in the Region realized with public contribution under the supervision of Regional Technical Service Offices, whose duty is to verify testing operations, compute money, collect the production or consumption electric energy monitoring data.

In paragraph 7. *Presentation of some results in PV production (results at open air)* are illustrated some results collected in a voluntary work, that should be an aim for institutional research activity in the territory. A reminder foreseeing policy to sustain research in the field of electric energy production from renewable sources with clear aims and fair financial means.

Last paragraph 8. *Technical, economic and political perspectives to sustain PV technology diffusion* is a synthetic report about difficulties and expectations opened in Region and in Italy from public announcements to sustain PV technology.

1. Elements about electric properties of solids

1.1 Metals, insulators and semiconductors. It's well known that this distinction is due, from the microscopic point of view, to the rules that establish the way in which the electrons are arranged in atomic orbitals, and from the macroscopic one to the value of electric resistivity (or conducibility).

The materials of which PV cell is composed belong to the semiconductors class (not pure). Let's consider, also, that PV cell employment requires metals and insulators. The conductor materials are used to draw grids to pick up the electric charges forced by light and to build metal contacts to flow the electric current. The insulator materials are used to encapsulate PV cell, both to resist against impact and to make easy the installation, and to prevent from electric current loss. In order to understand PV cell physics we should recall principles and laws that have been stated since when Max Planck[5] introduced the idea that hot objects emit and absorb light in little packets of energy called photons, irreducible quantities of energy. There is a notable scientific literature, both in text format and multimedia technologies that has made didactically affordable this sector of physics. But nevertheless it's impossible to conceive the difficulties whoever affords this kind of physics. It's not easy to find accessible models of the macroscopic world that make these ideas intuitive from phenomenological analogies and this before considering convenient abilities into mastering mathematic formalism if we wish to improve the understanding of these studies. We will skip this aspect of physics turning the reader to the bibliography.

In the next paragraphs we will hint, instead, the effects that take place on the microscopic level and have direct and evident consequences on the macroscopic level with physics quantities useful to compute and measure electric energy production. In others terms we will dwell upon essential parameters and physics laws that derive from a few reflections over electric conductivity in materials whose aim is a deeper knowledge of electric energy production in PV cells in small and large systems.

2. Semiconductors conducibility

2.1 Pure or intrinsic semiconductors. Pure semiconductors show two main differences respect to metals. If we apply an external electric field to a pure piece of semiconductor material, we find out a very low electric conductivity or, on the reverse, a much higher resistivity than in metals. Besides, the increase of temperature products in the semiconductors an opposite effect respect to metals, that is an increase of conductivity and a decrease of resistivity. In a certain way, as justified by the discoveries of "modern physics" (...the twentieth century physics!), semiconductors are "incomplete" insulators. In fact, at zero absolute temperature, insulators and semiconductors have the same electric properties.

Early scientists and technologists didn't know how to make them interesting to useful applications. Even today, in a mature technological age, scientists and technologists don't perform clearly in predicting useful applications of scientific research. It often happens, also in well disciplined fields of human endeavour, that "un foreseen consequence" takes place thanks to discoveries performed in a field of research completely different. The history of PV cell technology also shows "unintended consequences" that have improved the development of PV technology coming from researches that had different aims.

So, at the end of the first half of twentieth century the electronic industry became to deal. A fruitful field was the electric elaboration of signals in the automatic compute machine. The research of quick and affordable devices to interrupt and deal electric signals to substitute electro mechanics devices pushed some scientist to study deeply properties in some semiconductors.

The most interesting semiconductor material both for these researches and future perspectives in the rising of electronics industry was silicon (chemical symbol Si), one of the most plentiful elements in nature. Silicon, like germanium, is an element in Group IV of the periodic table (Z = 14), is a grey blue solid, has a metallic sheen and a specific density of 2.42. It is hard and brittle, melts at 1412 °C and is chemically reactive. Silicon is found in mineral forms (oxides, silicates). The reduction process is dealt with carbon in an electric oven with temperature in excess of 1500 °C to produce silicon with a purity of about 98%.

The brilliant idea to obtain a higher increase of electric conductivity in pure silicon was to spread inside the crystal, with particular techniques, elements of the nearest chemical substances in the periodic table of elements.

A semiconductor dealt in this way is said "doped" or "not pure". If one of these layers of Si crystal is doped with pentavalent substances, becomes a carrier of n charges (Si-n), if, on the contrary, it is doped with trivalent substances becomes a carrier of p charges (Si-p). The n charge carriers are the *electrons* while the P ones are called *holes* and are positive charges. These holes are not properly electric charges but the mechanism of electric conductivity in the crystal layer can been explained as if, instead of electrons, positive charges move along the material in the opposite versus.

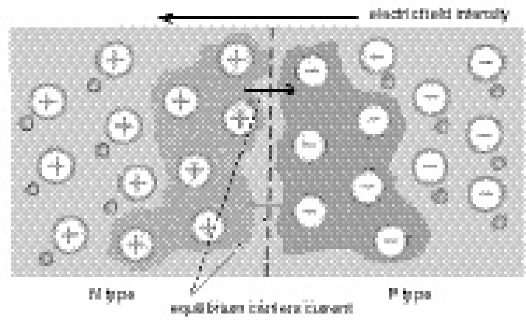


Figure 2.2.1. Distribution electric charge into the junction.

2.2 The P-N junction. If two P and N semiconductors layers, with no external voltage, are faced each other, electric charges of the two layers diffuse, as happens whenever there isn't balance of density of gas or liquids in two communicating volumes. Some of the free electrons from the N-type material diffuse across the junction P-N and recombine with holes in the lattice structure of the P-type material; similarly some of the holes in the P-type material diffuse in opposite direction and recombine with free electrons in the lattice of the N-type. These electric carriers, electrons from N layer and holes from P, are called *majority carriers* because they come from impurities: donors in N layer and acceptors in P. So, nearby the junction, two areas are formed, depleted of any electric mobile carriers: negative in the P region and positive in the N one. The P-type material thus acquires a slight negative charge and the N-type material acquires a slight positive charge (see Figure 2.2.1). This "transition layer" or "depletion layer", in which there are no majority carriers free to move, produces an electric field so that no more majority electric charges can cross the P-N junction. As a result of this recombination we find a "potential electric barrier" or an " intensity electric field" through a P-N junction. This electric field is intrinsic in a P-N junction and corresponds to a sort of "thermodynamics equilibrium" inside the semiconductor. The P-N junction is also called "diode" (see Photo 2.1).

There is an analogy with Volta's thought, that explained a "perpetual impulse", "action" or "motion" of the "electric fluid" achieved by the electric battery as the effect of an "electro motion force" produced by "…the Mere Contact of conducting Substances of different Kinds".

The difference respect to the electric battery is that the two metals chemically different (i.e. zinc and copper) are substituted by two P-N semiconductors layers with different doped density.

Another substantial difference with the electric battery, that hasn't an explanation in classical physics terms, lies in the moment we are trying to find, also with very sensitive instruments, an electric current in a

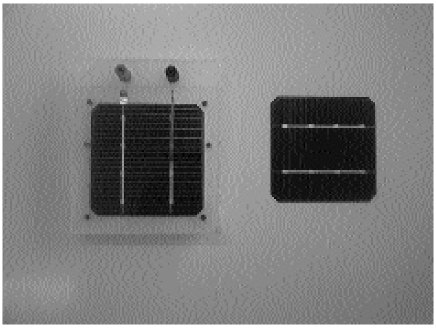


Photo 2.1. ITI "A. Malignani" laboratories: assembled and naked PV cells (courtesy *Masotti Energy Service Company*, Udine).

conductor wire joining the opposite P and N layers of the diode.

In the electric battery, the electric unbalance (an electric field) in the separating area between the two metals, keep a steady electric current of electrons flowing through a conductor wire joined to the opposite poles of the electric battery[6]. On the contrary, the electric field in P-N junction is unable to force an electric current in a closed circuit.

We obtain an electric current in an external circuit from a P-N junction in two ways: a) *biasing diode with an external electric supply*; b) *exposing one of the junctions surface to light*.

A deeper hint to P-N junctions before considering the basic physical process through which a junction (a solar cell) converts light into electricity.

In the semiconductor, at room temperature, an intrinsic production of electrons and holes is maintained because in the atoms the thermal energy vibrations can randomly break covalent bonds. These electric carriers, called *minority carriers*, are pushed from the electric field through the P-N junction, electrons from P to N and in the opposite sense the holes. In effect also majority carriers tend to diffuse across the junction due to a decrease of the intensity electric field produced by the minority carriers, but they are continuously repelled by the slight negative charge induced in the P-type material and the slight positive charge induced in the N-type material. The result is, at a steady temperature, an equal electric current value diffuse in an opposite versus and consequently no electric current flows through the junction.

The following facts can be described in a more effective way with quantum concepts. After the contact between P and N regions, *Fermi levels*[7] in the semiconductors must be drawn at the same level E_F in all the semiconductor. So the conduction and valence bands in the P region increase their energy respect to N region of a quantity qVo (Vo is the so named contact or electric barrier voltage). The amplitude of Vo depends on a certain fixed temperature, on the position of Fermi level respect to the bands and also on the doping levels in the two regions before the junction has been formed.

In this condition electrons and holes (majority carriers) flowing through P to N and viceversa are equal to holes and electrons (minority carriers) flowing from N to P and viceversa.

If we suppose to bias a P-N junction with an external electric generator with polarity + to P positive region and polarity – to N negative region, the electric generator potential reduces the potential barrier (V < Vo) with Fermi level displaced near the conduction band. As a consequence there is a greater number of majority carriers which flow from P to N and vice versa that overwhelm strongly minority carriers of thermal origin. Under this condition, the P-N junction is said to be *forward-biased*.

When the junction is biased with the same electric potential but in opposite way, with polarity – to P region and polarity + to N region, the barrier increases (V > Vo) and Fermi level is neatly displaced far from the conduction band. The result is a remarkable decrease (exponential) of the flux of majority carriers. Otherwise the minority carriers, basically of thermal origin, are not influenced. Under these conditions, the junction is said to be *reverse-biased*[8].

In both cases the result is: in the former one a strong conduction of electrons in the external circuit if the P-N junction is forward-biased, in the latter one a small, negligible conduction if P-N junction is reverse-biased. This anomalous electric conduction (non ohmic) is useful when diodes are applied in engineering[9].

The substantial difference between the PV cell, called also photodiode, and the diode is in the type of "electro motion" that pushes electric current into an external circuit. In the normal diode the "engine" is "forward-biased electric tension", otherwise in PV cell the "push" to produce electric flux is a sort of "electric current generator" fed by the radiation striking the diode surface exposed to the light photons. To summarize with a flash what we said before, the reader is invited to see Figures 2.2.2, 2.2.3, 2.2.4.

2.3 Photovoltaic effect. The invention of the electric battery followed a fruitful interaction between physics and the life science. As reminded in the previous paragraph, Volta's discovery made available for the first time a steady electric current caused by an "electro motion", or, in modern terms, an electric difference voltage. Volta's idea was profitable nevertheless not founded on a modern concept of atomistic structure of a matter. It was an idea raised in a century characterized by the concepts of "useful knowledge" and "quantifying spirit" in the age of enlightenment and under the influence of Newton's distance force action theory.

We can define electric battery as a paradoxal invention: an underlayer full of scientific and fruitful concepts and in the same time an object technologically rough. To interpretate photovoltaic effect and to build PV cell was necessary an enrichment in scientific astonishing concepts as Volta's battery was, but also a technology built on a new revolutionary basis.

In the previous paragraph we have mentioned the fundamental Planck's hypothesis that a hot object emits and absorbs photons of light. The idea of separate quanta of energy transmitted or asbsorbed by matter was not incompatible with the wave model of light propagation. But Einstein's suggestion in 1905, that light travels through space in the form of indis-

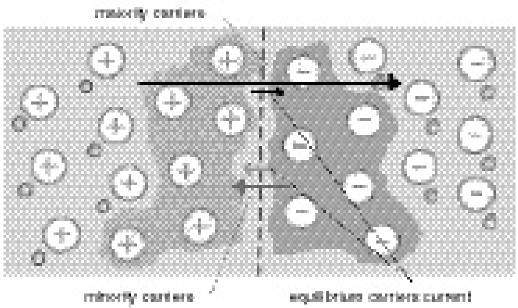


Figure 2.2.2. Forward biased P-N junction.

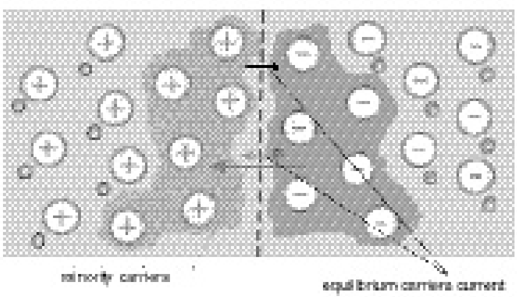


Figure 2.2.3. Reverse biased P-N junction.

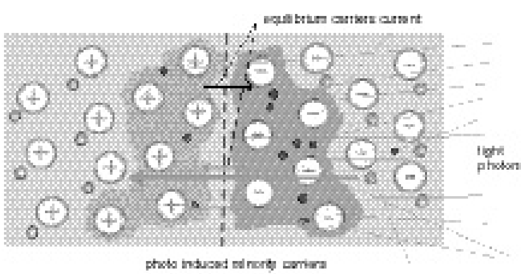


Figure 2.2.4. Photo ionized P-N junction (PV cell).

tinct photons, elicited incredulity from his contemporaries. In other words *the energy of the light is not "quantized" only when interacts with matter but it is in nature*. The quantum theory of light is strikingly successful in explaining the photoelectric effect. In photoelectric emission, photons of light provide the energy required by an electron to escape, as it happens in thermo ionic emission. In photoelectric emission the minimum energy required by an electron in order to escape from a metal surface states that: $E = h \cdot \nu$ ($h = 6{,}67 \cdot 10^{-34}$ j·s), where ν is the light frequency for ideal surface where function work is equal to zero. This model of light propagation explains why there is a frequency threshold and why the electrons current intensity emitted from metal surface, when extraction voltage is different from zero, depends both on frequency and on intensity of radiation and it does not depend only on the intensity.

This concept is immediately extended inside the semiconductor when a photon strikes on it but with differences compared to thermo ionic effect. If the frequency ν of the radiation is such that the energy of the photon E associated is greater than the energy gap between the upper limit of the valence band and the lower limit of the conduction band, then the radiation can be absorbed by the solid[10]. When electron/hole pair is created, a positive/negative ions is formed.

The photons that produce "ionisations" inside semiconductor dominate all the spectrum from a threshold infrared to violet until X rays and over (see Figure 2.3.1).

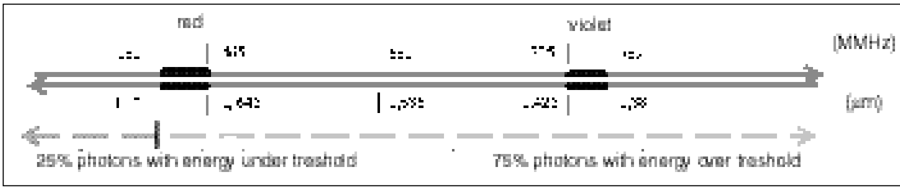


Figure 2.3.1. Radiation spectrum.

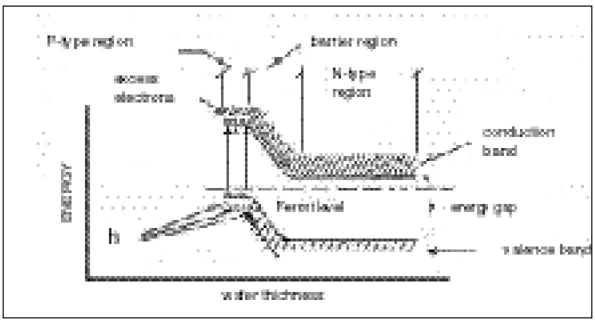


Figure 2.3.2. Photo diode conduction (PV cell) in bands quantistic model.

In the visible electromagnetic radiation there is a lot of energy per frequency unit. A photon with E = hν energy that exceed a typical gap band associated to a semiconductor can produce electron/hole pair. The ionised photons that strike in semiconductors near the P-N junction are more fruitful than the others because electron/hole pair have a good probability to cross the material and to be collected by grid. Electrons/holes so produced increase minority carriers of many orders while majority carriers stand in constant value. This is because donors and acceptors substances have already yielded their electrons and holes[11]. In Figure 2.3.2 P layer is exposed to light and that means that Fermi level is displaced close to valence band.

Minority photo induced carriers are in excess respect to normal thermal equilibrium density and then a electrons/holes minority carriers pairs quickly diffuse through voltage barrier pushed by the electric field. If PV cell is connected to an electric load a strong intensity electric current of minority carriers flows through a P-N junction and consequently a proportional intensity electric current of electrons flows to the load. The result is a strong increase of intensity electric current. But, as here we will see, there are remarkable differences between PV cell and diode.

While the flux of carriers in the forward bias diode electric current inside the junction is from P to N (*forward current*), in the PV cell is in opposite direction (*inverse current*). On the contrary there is no difference in external circuit because the electric current is a flux of electrons, so that the voltage applied to a load is like a junction forward biased but with opposite sign polarities on the electric contacts.

Few words to consider unloaded and loaded PV cell output voltage. Until no electric current flux runs, output voltage is the junction voltage Vo. But when PV cell is turned on the load a voltage drop happens and an electric current intensity flows through electric contacts joined with external circuit. If light intensity changes the electric current intensity changes in an approximately proportional way (Figure 3.1.1). What we have considered regarding PV cell is also available on PV module (see next paragraph). There are instead remarkable differences in the electric contact voltage change (or the load voltage) if we consider the behaviour of PV cell in temperature compared to a normal diode.

When we consider electric current in materials, everyone expects any device utilizing semiconductors to be sensitive to temperature change, and PV cells are no exception.

An increase in temperature produces in the semiconductors normally an increase of current, but also, on the contrary, a decrease in the voltage electric load. The main voltage change that one observes with respect to a diode is due to the fact that the increase of minority carriers due to temperature has a little incidence on the high value of total intensity current when the cell is exposed to light. Instead, we will find an opposite result if you consider the load voltage. As the junction temperature increases also electric current and the resistance inside a PV cell increase that means a strong voltage decrease.

In strict terms, in the PV cell, differently from the diode, voltage decrease prevails in negligible electric current increase due to minority carriers, especially if intensity light is strong. The conclusion is: a remarkable decrease of electric power.

In the next paragraphs we'll see that this result influence negatively the PV plants efficiency.

2.4 Some considerations about PV technology efficiency. Brilliant and firm theory, coherent with laboratory results, doesn't produce automatically a satisfactory technology development convenient to sustain an industrial production. In the fifties sophisticated techniques were set up by the same old brave technology pioneers and dreamers and business men candidates, to spread impurities into the crystalline. There are different techniques to inject impurities. Let's consider two techniques: the former consists to diffuse or to sprinkle a convenient layer of light transparent metal on the semiconductor surface; the latter, from the sixties the most employed, consists in forming P-N junction on the slice of silicon at a high room temperature (1200 °C) (epithassial process). The wafer layer exposed to light is thinner than the other in order to permit photons strike deeply near the junction and so avoid recombination of charge carriers[12].

Most largely PV cells that compose PV modules (called also panels) are derived from mono or multi crystalline layers of silicon; consequently all physics considerations in this paper implicitly refer to PV cell based on technology of crystal silicon. Si monocrystal production process to realize PV cells is expensive[13]. In a module PV cell is incapsulated and when the light strikes on it the radiant power Ir (Wm^{-2}) is converted into electric energy W (Wh).

Outside the atmosphere the light spectrum is like "black body spectrum" at a 5760 °C temperature. The power calculated with Stefan Boltzmann law is 1353 Wm^{-2}. This intensity is calculated at AM0 (Air Mass 0). But at sea level AM1.5, and depending on latitude, the atmosphere absorbs about 350 Wm^{-2} and then we must account an intensity radiation equal to 1000 Wm^{-2}. However, the modules in outdoor working conditions, once installed, could perform differently respect to laboratory conditions and, therefore, it's advisable to find out the variations of the parameters that may occur in order to carry out the pertinent corrections in calculation. In particular, the spectrum radiation profile is unevenly drawn (see Figure 2.4.1) while the characteristic of radiation black body spectrum has a regular profile and the experimental data are approximated by Planck law.

The main parameter to compare productivity in a Si mono or multi PV cell is the *efficiency*: a ratio of solar energy solar radiation transformed into electric energy.

If we observe Figure 2.3.1 we gather the possibility to convert 75% light energy into electric energy. Unfortunately energy surplus don't pro-

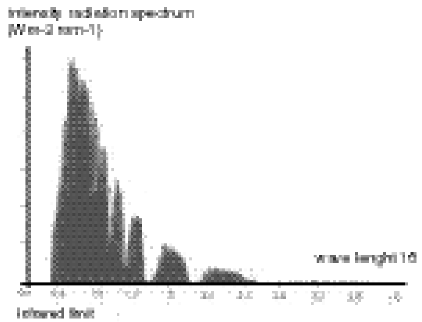


Figure 2.4.1. Solar spectrum.

duce new electron/hole pair but heath. Moreover, other factors decrease the efficiency of PV cell as we will see. Conversion efficiency depends on the property of the material we use, and for commercial Si mono and multi PV cell, the value is from 12% to 17%. The limit in PV efficiency, beyond the physic limit due to photoelectric phenomenon, is inherent to a particular technological process to build the PV cell and PV module.

The main factors that decrease the theoretical efficiency are:

- photons which produce electron/hole pairs with a surplus energy (E > Eg) don't produce new electrons/holes pairs but heat;
- some photons produce electron/hole pairs distant from P-N junction and then they recombine;
- some photons are reflected;
- part of electric current flux inside the cell produces heat;
- some electrons lose energy inside the cell for the collisions against lattice ions.

Here we develop considerations about the efficiency, the most "popular" parameter when we consider energy PV conversion.

The maximum PV efficiency value is:

$$\eta_{max} = K\cdot(\lambda\cdot V_{mp}/(1+\lambda\cdot V_m))(n_{ph.}(E_g)\cdot V_{mp}/(N_{ph}\cdot E_{av}))^{14}$$

K *constant depending on the reflection and transmission coefficients and collection efficiency*;

V_{mp} *is the voltage delivered at maximum power*;

$\lambda = e/k\cdot T$ *being* k *the Boltzmann constant*[15], e *the electron or hole charge*[16] *and* T *the absolute temperature*;

$n_{ph.}(E_g)$ *number of photons that generate electron / hole pairs in the semiconductor with energy gap Eg*;

$N_{ph}\cdot E_{av}$ *input power where* N_{ph} *is the number of incidents photons and* E_{av} *is their average energy in electron volts (eV)*;

Since $K \approx 1$ and $\lambda\cdot V_{mp} >> 1$ the equation can be written:

$$\eta_{max} \cong n_{ph.}(E_g)\cdot V_{mp})/(N_{ph}\cdot E_{av})$$

and since $n_{ph} \approx 2/3\, N_{ph}$ and $V_{mp} \approx 1/3\, E_{av}$ an estimate of the maximum theoretical efficiency for silicon can be obtained directly yielding about 22%.

We have an interesting extension of this conclusion when monochromatic light is used with energy equal to the band gap. For example if $n_{ph} = N_{ph}$ e $V_m \approx 2/3\, E_{av}$ and $V_{mp} \approx 0.75\, E_{av}$ then the efficiency can be up to 75%. But in this case we lose all the remaining spectrum frequency.

The perspectives to overcome polycrystalline Si limits in conversion light electricity depend on new technological processes that are being dealt in the main world laboratories, above all in countries that are supporting the development of technologies founded on electric energy production from renewable sources (Germany, Japan). With the aim to improve crystalline Si efficiency the industry is proceeding to increase the quality of manufacturing (to improve picking up surfaces, automations, chemical process, etc.) and new technological solutions such as sinking electric contacts in order to reduce shadows, building ether junctions and focus devices. In space applications they are utilizing different materials from Si to settle many layers to capture light frequency selectively (PV *amorphous three layers cell* are affordable technologies already present in trade). On this route it's difficult to overcome the 40% efficiency threshold.

Another very remarkable technological concept consists in the photonic conversion: different materials layers in front of and behind cells in order to reduce or increase wave length of incident photons (therefore all radiations of black body spectrum should be utilized without loss of energy).

The other large area is based on the development polymeric organic cell. In this one the light creates electric carriers with very short interval time (very lower than life time in crystalline PV cell) to be conveyed on the selected charge type collectors and successively to electric load.

At present crystalline Si is without competitors above all for the certified stability that producers guarantee for this material. This is a very important factor for the financial support programs of the States and also for the market that needs to establish the economic gain and break even point.

2.5 PV cell characteristics. The PV cell module operates as the PV cell because it is an algebraic linear elementary system and then the total effect in a module derives from the single effect superposition cell by cell.

It's a remarkable outcome to observe that the intensity of current on an electric load depends only on a number of photons that strike on it (Wm^{-2}) and it's independent on electric load value (Ohm). This is true in a large interval of tension electric values from short circuit current (Isc) to values next to a maximum voltage value Vpm (as we will see with refer to Figure 2.5). The correspondence from junction current Ij to electric tension V applied to the junction is usually defined with the equation below[17]:

$$Ij = Io(\exp(eV/(kT)-1); \qquad (1)$$

where:
T *absolute temperature*;
Io *dark current or reverse saturation*
e *electron charg*e (or *hole*);
k *Boltzmann constant*;

In Figure 2.5 Isc can be many times the dark junction reverse current Io (Isc > 10 Io).

When PV cell is exposed to light, as we see in the portion of the curve in the fourth quadrant, the region of power generation, we can write:

$$Isc = I+Ij \qquad (2)$$

I *current in the electric load.*

If I = 0 then Vmax = Voc (o*pen* c*ircuit voltage*) and

$$Voc = (kT/e)\ln(Isc/Io + 1). \qquad (3)$$

If V = 0 then Ij = 0 and Isc = I (s*hort circuit* c*urrent*).

In Figure 2.5.1 when the PV cell is exposed to Ir (Wm^{-2}) the working point is in the fourth quadrant on the light characteristic.

In technical literature we find graphics translated to the (0,-Isc) as we see in paragraph 3 about "How PV module works".

Before considering the management and electric production engineering aspects in a working plant condition, we will still reflect on the general characteristics of a PV module.

The PV modules under STC (S*tandard* T*est* C*onditions*[18]) consider in particular the two electric values already mentioned before:

Isc (short circuit current): it is the maximum PV cell intensity electric current supplied. This intensity no longer damages the PV cell, on the

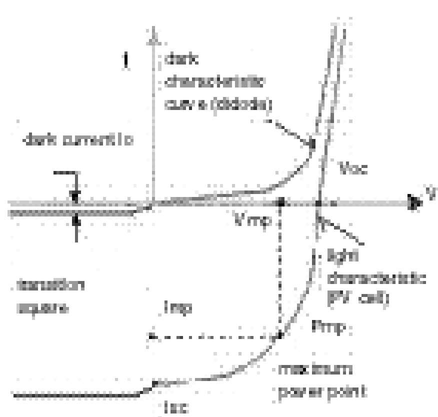


Figure 2.5.1. Current versus voltage characteristic in a PV cell.

contrary its value is 5 ÷ 15% higher than nominal current;

Voc (open circuit voltage): it is the maximum PV cell electric voltage. Its value is 15 ÷ 20% higher than nominal voltage;

and the following:

Vmp (maximum power voltage) or nominal voltage: it is the maximum voltage at maximum power point Pmp;

Imp (maximum power current) or nominal current: it is the intensity electric current at maximum power point Pmp;

Pmp (maximum power) or nominal power: the maximum power delivered represented by the largest rectangle that can be fitted into this area.

Some useful considerations to evaluate the PV module performance:

- nominal current value Ipm is near Isc value and normally not dangerous for the operator;
- PV modules characteristics are listed in a laboratory data sheet in steady conditions both in radiation Ir and in temperature T, while in external conditions Ir and T continuously change;
- during the conversion of light intensity into electric power in order to obtain the maximum yield of electric energy the electric load is fitted to P ≈ Pmp[19];
- PV cell yield is much higher: until 90% when an electric battery can reach about 50%[20];
- intensity electric current is proportional to light intensity;
- saturation voltage is reached when light intensity flux is maximum (useful property when PV modules are used to charge electric battery[21]).
- the squarer the current-voltage characteristic, the higher the efficiency (Pmp ≅ Voc. Isc).

3. How PV module works

3.1 PV module. Usually in a PV module we find 36 or 72 PV cells connected in series, end to end, + with – leads, to reach Vmp (maximum power voltage) and, considered that every square centimetre produces from 12% to 14% of solar radiant power in STC, PV cell surface is built to produce Imp (maximum power current) per string. It's easy to calculate Pmp (maximum power) or nominal power from the product of strings current and voltage.

In Figure 3.1.1 is represented a family of three external characteristics with current I(A) function of voltage V(V) each determined with a specific intensity of radiation Ir. Every couple of coordinate (I,V) represents a particular value of electric load and consequently an electric power P = VI (W). With Ir = 800 Wm^{-2} the point on the characteristic of coordinates (Imp,Vmp) corresponds to a particular electric load on the characteristic curve.

There is a twofold perspective under which to evaluate PV module behaviour.

First: *Isc/Ir rate is a constant value*, and the electric current I maintains a steady value until near maximum power point on the knee of the characteristic (see Figure 3.1.1); this means also that the graphical relationship between power P and voltage V is a straight line as shown also in Figure 3.1.2). This result has a microscopic explanation: intensity radiation is proportional to useful ionising photons numbers that produce a proportional increase in electric conductibility. This is due to the fact that the increase of minority carriers is exponential while the increase of majority carriers is little respect to the total number of majority carriers in the material that are already free at room temperature. In other terms the electrons/holes minority carriers generated domain the electrons/holes majority carriers. The macroscopic result of the microscopic events is shown with a straight line to Isc circuit short current point until the knee near a Pmp maximum electric power. For the PV consumer the module acts in the same way as if an electric current intensity flows independently on the electric load value.

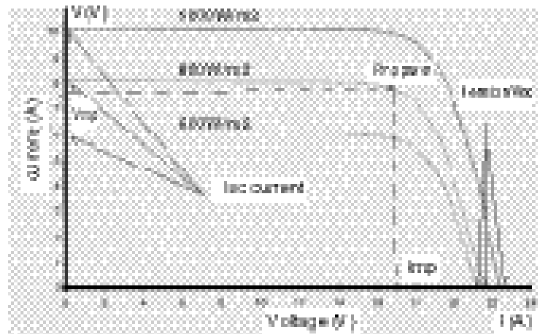


Figure 3.1.1. I versus V variation curve as a function of incident solar irradiance at constant temperature.

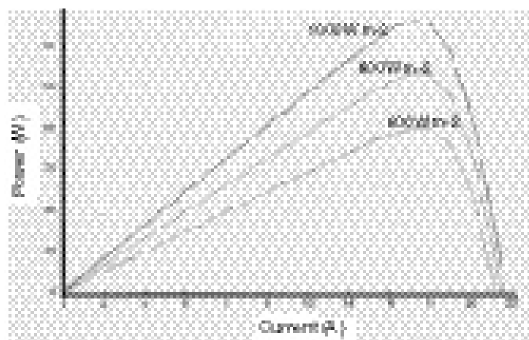


Figure 3.1.2. P versus V variation curve as a function of incident solar irradiance at constant temperature PV cell.

In practical situation this consideration must be evaluated and adapted.

In grid connected PV plants the conversion DC/AC (Direct current/Alternating current) is made by an electronic apparatus called *inverter* or *converter*. It works following power maximum Ppm point where intensity current Ipm is a little lower than Isc; with respect to this, the real behaviour is a good approximation to ideal electric current generator. In PV plants connected with electric accumulators, the working point depends on the state of the electric charge of the electric battery and on the electric characteristic of the batteries. An efficient charge process, with working point on the left of Ppm maximum electric power, is a result of a correct interface among the part of the system that compose PV plant: PV modules, charge regulator and accumulators. In paragraph *5 PV Plants. Technical scheme and considerations*, some criteria are illustrated for a correct assessment in PV plant engineering.

Second: *Voc open circuit voltage depend directly on the intensity radiation Ir.* Also this effect has a microscopic explanation. If PV cell isn't connected to an electric load, when the light strikes the P-N junction, the electrons/holes minority carriers production increases strongly, and this produces an electric inverse current through the P-N junction and a tightening of the barrier length. As a consequence holes/electrons majority carriers flow through a barrier in an opposite direction until a new equilibrium is reached at a higher Voc. When PV cell works and a current flows to an electric load, the electric voltage on Voc leads drops to a V load value because of grid and contacts electric resistance. When PV module works the change of Voc due to a change in light radiation intensity Ir is practically negligible. Consequently we can consider Voc a constant value. Instead, the direct dependence of Voc from Ir value is utilized in a lot of inverters in grid connected plants (see paragraph 5), to connect PV field to a public grid (ENEL) when the light intensity overcomes a fixed threshold.

3.2 Dependence of current and voltage on temperature. The efficiency of a PV plant strictly depends on temperature. It is a consequence of the fact that in a semiconductor at a microscopic level the conductivity is strongly dependent on temperature. Whilst a PV cell generated current is proportional to the intensity of solar radiation, the voltage varies with cell temperatures. Both effects are shown in Figure 3.2.1. It must be born in mind that the temperature of the PV cell, which we have been referring to, does not coincide with the room temperature due to the PV cell heating up when sunlight falls hereon. The increase in the PV cell's temperature compared with the air temperature depends on its characteristics and the actual characteristics of the PV cell itself. If temperature increases the effect is a noticeable voltage decrease Voc (and also Vmp), while the intensity of a current stands approximately at constant value. In strict terms a weak Isc increase is calculated but not sufficient to balance the strong decrease in voltage (see in Table 3.1 the negative temperature coefficient of Isc) and consequently we find a decreased Pmp. Moreover, if the module works at Ppm working point the current percentage intensity decreases (see in Table 3.1 the positive temperature coefficient of Ipm)[22]. In conclusion the squared Voc·Isc power decreases.

In the following lines are reported some considerations at microscopic level.

First of all let us consider that it is impossible to measure total electric current through P-N junction because electrons and holes continuously recombine inside semiconductor material. We can only indirectly derive the intensity electric current from Isc value. Let us follow some considerations to evaluate the temperature influence on electric current and on voltage.

First step in this topic one proposes a practical help for a better understanding at microscopic level of the parameters involved when temperature changes. The simple microscopic model one can use is a semi classical microscopic "free electron gas" model where the electrons are practically free from their original atoms to move in the crystal lattice formed by the ions. In PV cell the electrons are replaced by minority carriers.

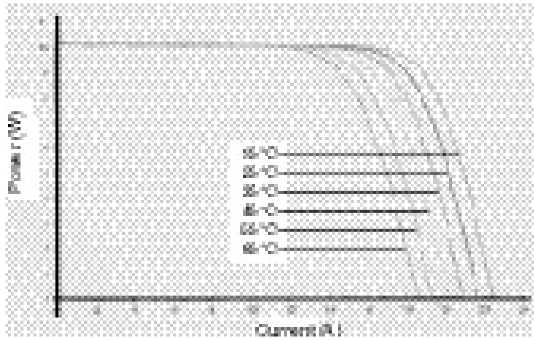


Figure 3.2.1. I versus V variation curve as a function of the PV cell temperature at constant incident radiation.

Minority carriers to perform an electric current in a external electric circuit must shift Vo barrier. The length path of minority carriers depend on life time. If μ is charge minority carrier *mobility* then μ = vd/E (with vd *drift velocity*, t *average life time* and E *intensity electric field*) then *path length* will be: L = μ τ E.

One sees that if we wish to have a high value in charge life time to have good probability to run out the PV cell, then we can change – at constant electric field intensity E – either the mobility value or drift velocity value; therefore the incidence of temperature on conductivity must pass through these parameters.

If we consider Einstein's equation: V = D/μ (D drift constant, V = kT/q with k Boltzmann constant) the mobility can be written as: μ = D/V. If we replace the ratio the consequence is: L = μ τ E = (D/V) τ E; if we consider that E = V/L follows L = sqrt(τ D). In Einstein's equation after having substituted μ we obtain: D = μ (kT/q).

A first conclusion: D is proportional to T but L is a function of square root D and then we can consider L practically independent on temperature.

If now we consider life time τ, a classic statistical consideration brings to the equation: τ = τo (1 + exp((Vt – V_F)/kT)) ≈ τo (Vt *trap voltage* and V_F *Fermi level*) practically independent on temperature if we consider a value range normally from -40°C to +80°C.

In conclusion Isc, for our aim, is temperature independent. Theory is in a good agreement with Figure 3.2.1

Second step Here we consider the influence of temperature on voltaic P-N junction Vo or Vmax = Voc when light strikes on it. In paragraph 2.4 in an ideal P-N junction in a PV cell the maximum voltage has been written as:

$$Voc = Vmax = \cong \ln (Isc / Io + 1)$$

That derives from equation (3) when I = 0. Considered that Isc is practically temperature independent, Voc is proportional inversely to T because proportional directly to approximate value of ln(C/Io) (Io increase as T); then at finally Voc can be written as follows:

$$Voc \cong \ln(C/Io)$$

Where the argument of ln(C/Io) decrease if T increases. The conclusion is in agreement with Figure 3.2.1. The value change of Voc influences directly the Vpm value. As we shall see in paragraph *5. PV Plants. Technical scheme and considerations* is very important to calculate the *power tolerance* and temperature coefficients.

Here are reported a data sheet model after having considered a certain number of data sheets furnished by manufacturing firms:

Table 3.1. Typology: *multi mono crystalline module.*

Electric parameters in Standard Condition (STC)	
Nominal Power (Pmp)	W
Power maximum tolerance (ΔPmp)	%
Minimum guarantees power	W
Nominal voltage (Vmp)	V
Nominal current (Imp)	A
Open circuit voltage (Voc)	V
Short current circuit (Isc)	A
Module efficiency	%
Cell efficiency	%
Isc coefficient temperature	+ %/°C
Voc coefficient temperature	- %/°C
Imp coefficient temperature	- %/°C
Vmp coefficient temperature	- %/°C
Normal cell operativity temperature (NOCT)	°C

3.3 PV field in an electric PV plant. In a PV field of an electric PV plant, modules are composed like PV cells: series of modules compose a string and paralleled strings compose a PV field. The number of modules and the number of strings depend on engineering factors. Some considerations are here developed to show aspects that are present at every electric plant of the builder before installing PV modules.

Usually maximum power Pmp is a project data to compute the need of energy electric annual production. In Pmp there are two factors Imp, Vmp strictly dependent. Chosen one, the other is imposed from Pmp value. At this point it is necessary to consider a typical PV plant: PV grid connected. In a PV plant grid connected the apparatus which interface the PV field with public grid is the converter (or inverter). Inverter is a converter DC/AC that works mainly in electric voltage. The inverter is characterized mainly by Pmp DC power and Pmp AC power on one hand, and by a "window" of electric tension ΔV = Vmax – Vmin on DC side on the other hand. Consequently the number of modules in a string produce a Voc whose value will fall on the window higher than Vmin and lower than Vmax.

In conclusion optimum result in term of a quantifying electric energy is a consequence that is a compromise between costs and electric parameters. "When all is said and done" there are two elements to evaluate the correct assessment and efficient conversion: a "high testing value" that means a power measurement close to a nominal power certified and a "customer satisfaction" that means a noticeable money save in terms of electric energy compensation.

3.4 Module productivity and meteo and geographical variables. Considered a certain type of module, the productivity depends mainly on these factors: latitude, morphology, meteo conditions. Beside environment situation, electric power depends on module exposition, that is on the quantity of surface exposed to light. If we consider the angle between normal direction at the surface and the rays sun direction, the maximum electric power is reached when the angle is zero degrees, considered steady all the other environment factors. With fixed module position, the angle is function of a day hour and season. At noon the angle is called *azimuth*. If azimuth is zero PV plant supplies maximum daily power. It is possible to compute exactly the slope of the module on a plane support (*tilt* angle) on the two solstices and two equinoxes: spring, autumn and summer, winter. In Friuli, where latitude is about 46°, the two angles corresponding to summer and winter equinoxes are about 15° and 60°. Considered fixed modules, tilt angle is chosen with a value intermediate between the previous ones. To maintain azimuth zero during sunny day the module must track the sun. This solution is ideal because in practice modules are leaned on the slope of the roof (*retrofit*).

The evaluation of productivity will require local data. At present softwares produce outputs with reference to large geographical areas while morphology and weather conditions are different. In our Region these environmental factors are very changeable: radiation and temperature change in a wide range passing from sea to mountain and from hills to alpine valleys. Also cloudiness, wet air, diffused radiation are very changeable and influence notably the productivity. In conclusion an accurate provisional planning energy production from PV plants, focused on a particular place, needs a more accurate project, measurements and Data Bases automatically updated with environment data transmitted from sensors net, thickly distributed on all the geographic territory of our Region.

4. "Agathos" project: experiences for an interactive science and technology didactics. The *Agathos* project was spurred by the 200^{th} anniversary of electric battery discovery Seminar in 1999. Afterwards it has been developed in different periods. Here

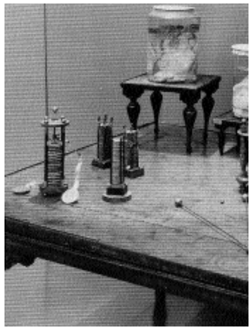


Photo 4.0. Part of a Volta work table with two torpedo in a glass bottle and a group of electric battery (courtesy *Museo per la Storia dell'Università di Pavia*).

we will mention some of the most important experiences.

At the beginning AIF Udine membership stimulated Udine Province to grasp the opportunity of "10 000 PV roofs" national programme, as a first step towards a new field of study and technological innovation, and suggested to install a PV plant at ITI "A. Malignani". Successively Agathos members, some of ITI "A. Malignani" teachers and technicians and some members of AIF Udine, have participated to UAT (Udine Alta Tecnologia) meetings and workshops to set up a special area in Udine for scientific education and entertainment. Finally one of the school teacher of ITI "A. Malignani" and Agathos member has participated to the workshop "Il Sole a Scuola" organized by ENEA (Ente Nazionale dell'Energia e dell'Ambiente – National Council for New Technologies, Energy and Environment) with MIUR (Ministero Istruzione Università Ricerca – Research University Instruction Ministry) and MINAMB (MINistero AMBiente – Environment Ministry) collaboration.

Inside the ITI "A. Malignani" different experiences have been started, also with students' collaboration, to build prototypes to promote scientific and technology learning. Electric Volta's battery was one of the most attractive prototypes, built up in occasion of 1999 anniversary. Later the attention was shifted from the so called "electric battery and its wonders", to electric production from PV effect.

Initially we have started to study the efficiency in amorphous Si little module (panel), then the single poli crystalline Si PV cell has been studied and at last an electric board interface was assembled to connect two PV poli crystalline modules to study electric energy production and saving. This last choice was fore-seeing because experience and measure sessions had been made before a special 5 kW PV plant was meant to be built in an external area of the school[23]. The advantage, in fact, has been twofold: on one side spreading the culture of energy electric production from renewable sources and promoting the attitude to sustainable development, and on the other hand students and teachers have started to make planning and research experiences in order to utilize clean and renewable energy power.

In this work, list of data and measurements are not showed, but some hints about motivations and methods adopted and short comments.

Let us start stating that outdoor measurements or "en plein air" are affected by a series of disturbance factors respect to comfortable and controlled laboratory measurements. The light before striking surfaces crosses the air mass of the atmosphere. Density air layer is almost instantaneously variable due to thermal excursion movement in the air mass and also for other less important factors. The consequence is an unstable or floating measure. As considered in paragraph 2 the sun spectrum of visible light in condition of AM1,5 is uneven and irregular[24]. This irregular profile depends on the different quantity of radiation absorbed in the atmosphere per frequency. Furthermore this profile is not stable but variable in function of air meteo conditions (see Figure 2.4.1).

These essential considerations on the environment conditions influence measurement process and lead to state that precision is not a strictly necessary factor to collect useful data to evaluate the efficiency PV conversion. Infact, even if not greatly precise instruments have been utilized, measurements "filtered" by this sort of "wide stitch grid", they have offered us precious and basically "correct" information. These results will be discussed above all in next paragraphs 6 and 7.

Efficiency evaluation in transformation process to *radiation energy/electric energy* has been reported thanks to "PV measurement table" and prototypes "PV islands" and "PV sunflower". The apparatus were built in ITI "A. Malignani" laboratories and working departments. For a simple and easy reading, the experiences are split in "blocks" also if, sometime, practical activities were dealt in parallel or in intersection.

I block. In this first part of pre-eminent didactical interest, oriented to improve interest in 15, 16 years old students, a background has been prepared for successive PV fields monitoring phases (see photo 4.1 e 4.2).

A little amorphous Si panel has been exposed to the sun radiation to obtain voltage and current data in function of electric load (a resistance sample electric box). Current and voltage have been correlated to obtain the external characteristic of the panel, to spot the maximum power Pmp and to calculate the approximate value of the panel efficiency. The measure has been made on 26 July 2003 in a time interval from about 12h and 15m to 13h. We have also

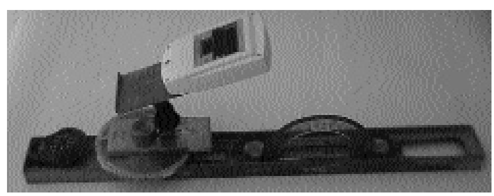


Photo 4.1. Didactical system to collect intensity-light radiation and temperature on PV cell: sunmeter and revolving support.

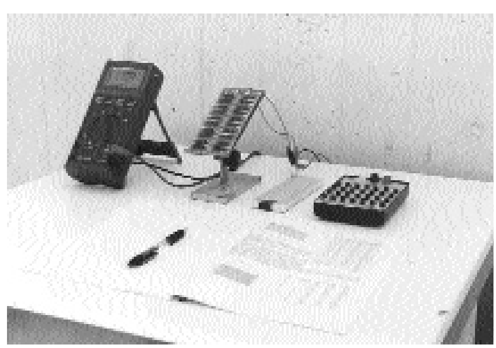


Photo 4.2. Measurement table "en plen air" to collect data from PV panel.

read ARPA – OSMER FVG Agency[25] files showing radiation measurements. The average measures reported in our session was approximately equal to the radiation in joule per hour furnished by ARPA – OSMER.

The apparatus has been positioned with an azimuth angle about 15° south east and with 30° on the ground level (tilt angle).

All the data measurement have been reported on excel data sheet to reproduce the PV panel external characteristics[26]. The point of maximum power was found on the knee of the curve characteristic: Pmax = 193, 3 mW; considered intensity radiation Ir ≈ 1000 W m^{-2} and net surface S = 28, 9 cm^2, the efficiency is calculated with the formula:

$$\eta = Pmax / Ir \cdot S = 6,65\%$$

a value that allows an indoubtable conclusion about the type of crystalline PV cell: amorphous Si.

II block. The students have been lead to manage PV plant problems thanks to the purchase of two 75 W nominal power modules mounted on mobile carriages. In this way transport and positioning modules have been made easy. Another carriage hosted the other electric components: a) accumulators; b) charge regulator; c) pure sinusoidal wave inverter.

Before starting measurement two aims were fixed. *First* to evaluate difference between nominal power and effective power on STC. *Second* to measure voltage/current electric quantities with series and parallel modules connected to accumulators.

The principle physics quantities involved in a measurement process have been:

– *PV module characteristics*: Ppm = 75 Wp, Vpm = 17, 0 V, Ipm = 4,4 A, Voc = 21,6V, Isc = 4,7A;

– *site*: Udine ITI "A. Malignani" 46° north latitude;

– *meteo condition*: bright and calm; day: 30/03/2004; interval time: 11h:15m – 11h:25m; air temperature: 21, 5 °C ± 2 °C;

– *PV modules set*: azimuth: about -5°; tilt: about 30°; Ir = 950 ± 1015 W m^{-2}.

The maximum value of electric power approximately STC with modules in parallel has been 126W about. A value about 15% lower than nominal value declared (75W per module).

A complete study with modules connected in series and in parallel has not been ended. Data should be gathered to define external characteristics with PV modules in series and parallel connected with accumulators in charge condition with or without charge regulator interfaced PV modules and accumulators. Finally, for a complete research, we should consider conversion efficiency in DC/AC conversion when the inverter supplies electric energy to an electric load.

In anticipation of a measurement session, and with the aim to facilitate and to quick data collection an interfaced electric board has been drawn and built (see Photo 4.4) with students and laboratory technicians support.

The other elements to complete the prototype "PV island":

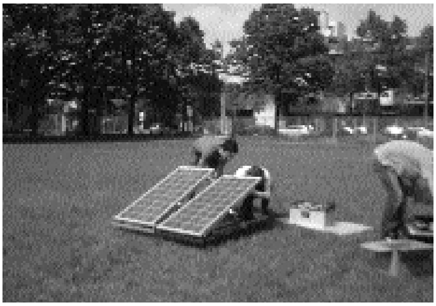


Photo 4.3. "PV island" asset in an "open air" laboratory.

Photo 4.4. "PV island" prototype in the main entrance room ITI "A. Malignani".

– *N. 1 charge regulator* 24 V/30 A;
– *N. 1 accumulator* Nb = 2/12 V Pb electric battery element sulphuric acid d = 1,2; 129AhC10, 119AhC5, 108AhC3, 108AhC5; 83AhC1;
– *N. 1 inverter* 200 VA pure sinusoidal wave.

Significant "outdoor" measures have been collected with:
a) PV modules and accumulator *interfaced with charge regulator* with 24 V DC electric load (gas electric discharge, DC electric engines) and with 220V AC electric load (AC asynchronous electric motor).
b) PV modules and accumulator connected *without charge regulator*.

After taking confidence with materials and apparatus, acquiring awareness about the relation between productivity and meteo conditions, system parameters asset, we have considered possible solutions to obtain maximum efficiency in the conversion from radiant energy into electric energy.

III block. Different systems were built to drive and to set PV panels and modules. With the first prototype, the so called "Copernicano sun flower" (see one of the mobile supports in Photo 4.5), they studied variations of electric productivity in PV small panels in function of the angles corresponding to the latitude and longitude of the site where modules and panels hypothetically will be set.

The second one, built in a school project, automatically tracks the sun by means of sensors and of a software of a PLC[27] (Photo 4.6).

A "PV sunflower" of commercial interest was visited by teachers (Photo 4.7), to start the planning for a mechanical part of 5 KW PV project in ITI "A. Malignani" in Udine (Photo 4.8).

Some consideration about the perspectives of this type of PV plant.

If on one side we obtain an increase of productivity higher than 30%, on the other hand we have to consider factors both economical and technical. Mechanical support to obtain an automated solar tracking[28] will increase tangibly the ratio euro/watt without a correspondent appreciable decrease of number of years to

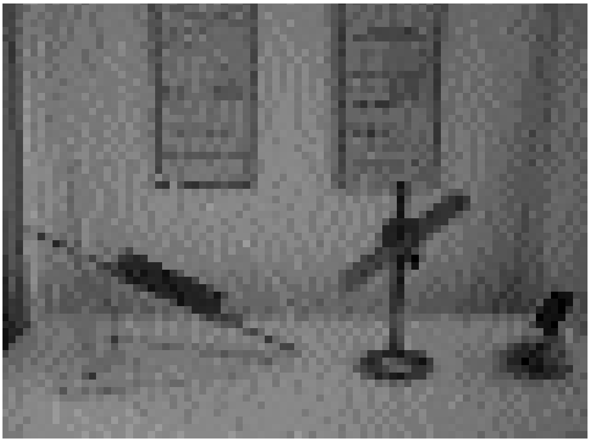


Photo 4.5. Didactical models of “PV mobile supports”.

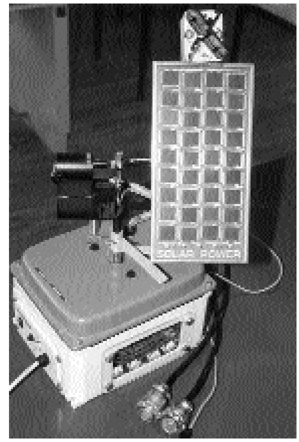


Photo 4.6. “PV sunflower” with sensors to track visible light of the sun.

allow a quick recover of the investment due to a greater production of electric energy.

Under the technical point of view, PV plant solar tracking needs both a solid base to fix metallic structure and engineering estimates to assure resistance against wind blast (sail effect).

Finally, let us remember “PV roofs” financial policy: the unit cost euro/watt fixed to calculate the ratio of financial share is referred to PV fixed plants on a plane roof; and in the case we wish to fix the structure on the ground level, the surface must have a “passivity” qualification, that means useless for agriculture or urbanity use (terrace under lattice-

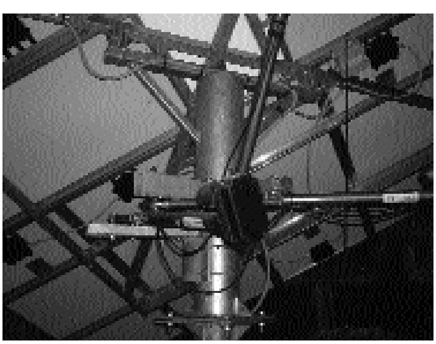


Photo 4.7. “PV sunflower” 0,5 KW: particular of the inside mechanical part to rotate modules (courtesy *Enerpoint srl* Milano).

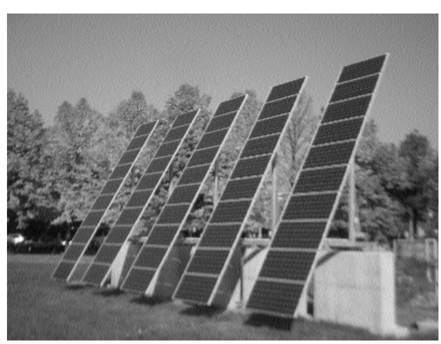


Photo 4.8. Double function 5KW PV plant built at ITI “A. Malignani” Udine with Agathos group scientific and project consulting.

works, polluted areas, road edges under ground level, etc).

However the study of electric energy production with a tracking plant is didactically very useful and interesting for the large people involved, students, teachers and professionals, and for the wide spectrum of the topics. On the other hand the perspectives to broad this typology depend on opportunity to insert PV plants innovative solutions inside pilot projects with a visible spin off appreciable to public opinion.

On applied research field, economical passive track systems are being studied (without programmable systems) and also static oriented system (concentrators and PV surface properly worked) to obtain surfaces aligned perpendicularly to the sun rays.

5. PV Plants

5.1 Technical schemes. Historically PV technologies have been used to produce small electric energy quantities in particular situations considered the impossibility to produce electric energy with other technologies or economic advantage to install PV modules where public net supply is missing[29].

PV plants to stock electric energy on accumulators are usually called *stand-alone*[30] and in the present financial policy sustaining PV technologies they occupy a market niche. They are installed where public net is not present and then it is necessary to convey electric energy produced when light strikes on PV cells to electric accumulators. The most present PV plant

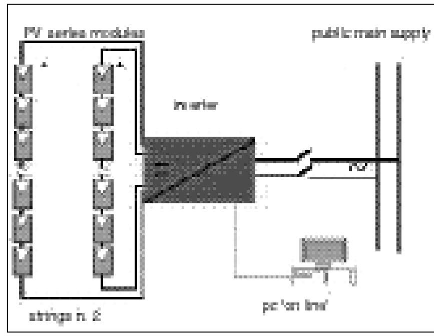


Figure 5.1.1. PV plant scheme GC.

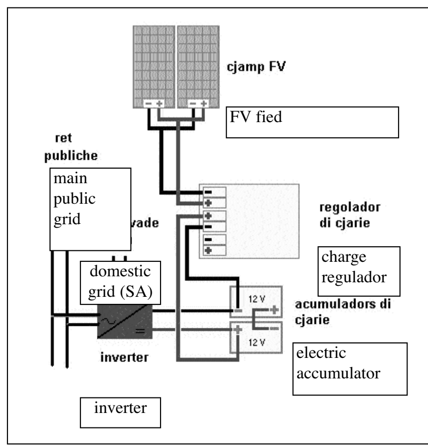


Figure 5.1.2. PV plant scheme double function GC and SA.

on beneficiaries list is *grid connected*[31]. This is comprehensible because in this type of PV plant all the electric energy production on PV roofs is utilized independently on power consumption, and so this permits a maximum energy saving. Here we hint another type of PV plant, scarcely widespread, with the property both to stock energy in electric accumulators and convey it into public net. This third typology that gathers both the previous solutions is called *double* *function*[32]. Therefore, in this last, the electric energy supply is available also if a *black out* happens.

In Figure 5.1.1 and Figure 5.1.2 are reproduced the schemes of the two most spread PV plants: a) PV plant grid connected (from hereon GC) b) a stand alone (from hereon SA). A remarkable hint to a special unit, already discussed in the previous paragraph, utilized in different configurations (GC or SA): the so named "PV sunflower" or "Sun tracker". It is not a new PV plant type but an expedient to improve efficiency in conversion process (about 40%).

The PV generator is not a complicated system to produce electricity (much less than a nuclear station…!) but the simple parts of it must be connected with engineering skill. Here we consider the main parts of 2 PV plants: a) PV panel or module; b) PV field built with a certain number of strings; c) the inverter, or converter, as control unit; d) DC accumulator composed with a certain number of electric batteries (added in GC-SA system or only in SA system); e) a field electric board (with electric protections in it); *f)* electric energy meter (not present in SA PV plants).

We should add an optional part: *h)* monitoring system.

Some considerations on monitoring system: inverters, usually, are able to maintain in memory maximum power (W), the daily energy, total energy (KWh) and working hours (h). But this is not sufficient to test PV plant and to evaluate efficiency. It is essential to measure also temperature (°C) and light radiation (Wm^{-2}). If the aim is, moreover, continuously monitoring and to save data and successively to elaborate them, is necessary that inverter, or a separate unit control, are connected with temperature and light sensors. A software built in the inverter or a "Data Logger" will transmit data to a synoptic square or an electronic calculator (commonly a personal computer shortly written "pc") for a prompt reading or for a batch elaboration.

5.2 Project hints. Before any other consideration remind the gold rule*: the closer the maximum power voltage we can make the photovoltaic module work, the greater will be the electric energy we shall obtain from it.*

In PV GC plant the inverter has integrated a software to follow in every load condition this goal (MPPT Maximum Point Power Track).

In PV SA plant this is an open problem: a challenge for planners!

An *optimum PV plant planning* depends on different factors. The main are: a) type model and nominal power b) how strings are composed (series and parallel); c) PV field / inverter interface; d) orientation of PV field; e) wiring solutions.

Now, some practice technical information to realize PV plant at "workmanlike" (considerations are referred to Table 3.1): a) nominal power is not effective and subsequently to evaluate energy production we must refer to minimum power at STC and, when temperature is higher than 25 °C, recalculate power if temperature coefficient is known; b) strings have to be composed with

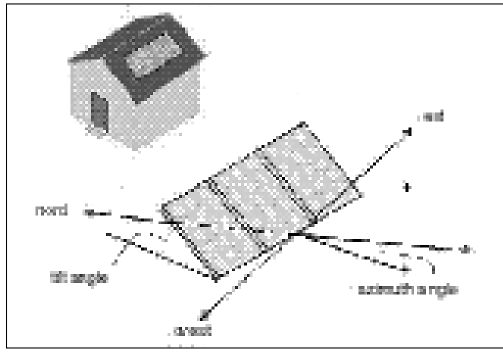


Figure 5.2.1. PV field orientation.

selected minimum power modules and with minimum variation of maximum power ΔPpm; c) two criteria must be present to choose an inverter: c1) the nominal power must be greater than maximum power furnished to PV plant, c2) voltage inverter window must contain interval output voltage ΔVoc[33] of PV plant with minimum voltage (Voc min) value calculated at maximum temperature and voltage maximum value (Voc max) calculated at minimum temperature equal or lower than nominal voltage output Voc; d) the choice of the best slope roof to install PV plant is south/south west oriented and obviously azimuth angle is imposed, except for PV modules installed on track structure where the azimuth is always maintained at utmost value; instead we can change tilt angle if PV structure is placed on terrace; on fixed structure tilt angle is a compromise between minimum angle (summer solstice) and maximum angle (winter solstice); the Δtilt angular change depends on site latitude (see Figure 5.2.1).

Further considerations to evaluate economic interest to install a PV plant.

PV module is a critical element to establish total cost in PV plant. The cost of PV field covers up to 70% ÷ 80% of total cost. So, as a consequence we will consider properties and performances in PV module.

At present PV modules trade is constituted above all by electronic degree crystalline modules. Si monocrystalline establishes an efficiency lightly greater than polycrystalline and so the latter has an efficiency in surface lower than the former. Amorphous Si is worth a particular consideration. Experts think that amorphous will begin to be employed if perplexity about its stability will be over. PV amorphous Si cells have about half efficiency than crystalline Si cell when light strikes on them; however, the efficiency of PV amorphous cell is better when we have diffused light. Moreover Si cells are cheaper and they can be fitted to every surface.

To summarize, we are interested to evaluate all this main variables in order to evaluate *PV plant productivity* and so be able to compute the number of months of PV plant activities necessary to balance the investment. To evaluate KWh product in a year is necessary to integrate instantaneous power. This operation is automatically executed by the *inverte*r and/or by *meter energy*. The energy meter is required by ENEL “Ente Nazionale per l’Energia Elettrica”

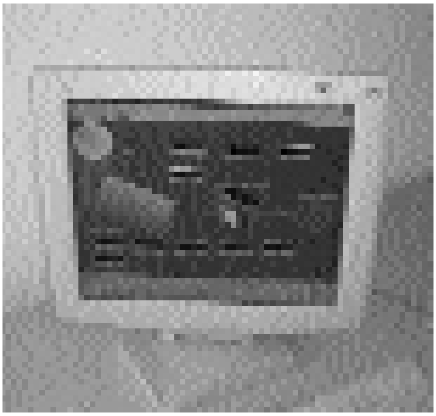


Photo 5.1. Computer (pc) "on line" to monitor PV production data collection.

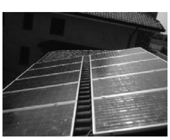
(National Electric Board) to keep account of in and out energy flow (the exchange of the electric energy on site).

One of the *research aim* in the future will be to collect data production from monitored plants installed in the main municipalities in the Region to compare data energy production with provisional data furnished from mathematical models.

One of the *project aim* will be efficiency improvement of PV module and at the same time a better definition of nominal power nowadays scarcely accurate and not profitable for installers and customers.

6. Some PV plants realized in Region with public contributions (First Public announcement in 2001). The total PV plants power installed in 2001 in Friuli Venezia Giulia Region is about 100 kW: half of them with Region FVG contributions set aside to private buildings and the rest from Environment Ministry set aside both to private and public buildings[34].

Here is a page illustrating some "PV roofs" on private and public buildings.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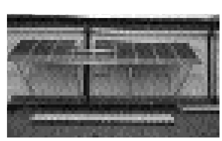
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Photo from left to right: photo 1. Dalmasson L. PV roof, Corno di Rosazzo (Ud); photo 2. Cecotti S. PV roof, Cividale del Friuli (Ud); photo 3. PV EuroJulia srl, Valle di pesca Francamella, PV field Grado (Go); photo 4. Pozzetto S. Sas, PV roof, Manzano (Ud); photo 5. AMGA Spa, PV roof, Udine; photo 6. Consorzio per lo sviluppo industriale di Monfalcone, PV field on level ground, Monfalcone (Go); photo 7. Cervesato G. sas. PV field on a terrace roof, Pradamano (Ud); photo 8, 9, 10. Town Hall, Gymnasium, Middle School, PV roofs, Comune di Montereale Valcellina (Pn).

Here are illustrated characteristics, components and production data from some PV plants installed with public financing. Here after we will consider the realizations divided in two clusters: *Comment* to discuss PV productivity compared with expectation and *Simulation* to compare the output data of the program with the results from elaboration of real data.

Dalmasson L. House, Corno di Rosazzo (Ud): historically is the first private PV plant GC started in Udine Province with public financing (14 August 2003). Drawn up and carried out by Ditta Pozzetto Silvio Impianti Elettrici sas Manzano (Ud).

Plant characteristic, components and production results: a) 20° slope roof on garage, ground height: from 4 m on top to 3,0 m on perimetral wall; b) number of strings Ns = 2, surface S = 15, 6 m^2; c) number modules Np = 12 NE-Q5E2E in Si polycrystalline Ipm = 4, 77 A, Vpm = 34, 6, Voc = 43,6 V, Isc = 5,46 A; d) N. 1 inverter IG20 until 2,5 KW on DC side; e) first year production 2054 kWh; f) equivalent hours: about 2,84 heq.

Comment. Production expectation: about 2300 KWh corresponding to 3,1 heq; lower production (about -10%) is due to different reasons. We can consider the main ones: a) a partial shading at sunset due to the near owner's house higher than PV roof together with the consideration that sunlight in sunset hours is more productive than with morning sun, a year cloudier than the average; b) effective power is resulted less than nominal power; with reference to a 156,8 W minimum power declared from the manufacturer, PV field power is calculated to 1800W that corresponds to 3,0 heq that is lower than 2,84 heq above mentioned.

Data monitoring has been read directly from the inverter (kWh, W e CO2), intensity data radiation and temperature (W m^{-2} e °C) have been read directly on the display of a sun meter with temperature sensor built in[35].

Simulation. Data input. City: Udine; latitude: 46°; inclined roof plane: 15°; Azimuth: -10°; consumption energy in a year (KWh): 2100; yearly intensity radiation (KW m^2): 1311.

Data output. Electric energy conveyed on grid (efficiency 78% ÷ 82%): 1022 ÷ 1075 KWh/y; The power PV plant we should install will be: 1953 ÷ 2055 KW.

Cecotti S. House, Cividale del Friuli (Ud): historically the first private PV plant GC from ENEL started in Udine Province (10 November 2003). Drawn up and carried out by Ditta Pozzetto Silvio Impianti Elettrici sas Manzano (Ud).

Plant charateristic, components and production results: a) 20° slope roof on garage, ground height: from 4 m on top to 3,0 m on the perimeter wall; b) number strings Ns = 3, surface S = 27, 3 m^2; c) number modules Np = 21 NE-Q5E2E in Si polycrystalline Ipm = 4, 77 A, Vpm = 34, 6, Voc = 43,6 V, Isc = 5,46 A; d) N. 1 inverter IG30 until 3,5 KW on DC side; e) first year production 3604 kWh; f) equivalent hours: about 2,85 heq.

Comment. Production result is superior to the expectation considered south west oriented slope roof with an azimuth on -60° (south west) and a tilt angle less than 15° respect to what is considered the optimum. On this favourable outcome we can rise some hypothesis: the slope, a few meters high over the ground, has been anyway well sunny by the sunset light without shadows against the skyline. Light in the afternoon, so rich of long lenght waves, results more efficient than morning light whose light wave length is shifted towards short waves. The consequence is that partial loss of radiation in the morning because of the slope, south west oriented, is not exposed directly to the light, decreases the total electric production of a rate inferior to what we expected. Finally meteo conditions in the area, with low diffused radiation, exalted PV polycrystalline technology.

Simulation. Data input. City: Udine; latitude: 46°; inclined roof plane: 15°; Azimuth: -60°; consumption energy in a year (KWh): 3500; yearly intensity radiation (KW m^2): 1266.

Data output. Electric energy conveyed on grid (efficiency 78% ÷ 82%): 968 ÷ 1038 KWh/y; The power PV plant we should install will be: 3543 ÷ 3372 KW.

Casa Pozzetto S., Manzano (Ud): PV plant GC joined to public grid by ENEL on 23 July 2004. Drawn up by Ditta Pozzetto Silvio Impianti Elettrici sas Manzano (Ud).

Plant characteristic, components and production results: a) 20° slope roof south oriented on building assigned to domestic and office use with ground height: from 7 m on top to 5, 0 m on the perimeter wall; b) Ns = 1 string with surface extension S = 17, 77 m^2; c) number modules Np = 14 model I165 165 Voc = 21, 6 V, Isc = 10,14 A, Ipm = 9, 48 A, Vpm = 17, 4 V monocrystalline Si, d) N. 1 inverter SMA SB1700E until 2500 W AC site e) on 30 December 2004 on a pc desktop screen we read: E = 903 KWh, th = 1720 hours.

Comment. PV system is monitored and conventional quantities are reported on a pc desktop (kW, kWh, th, CO2, ecc.) transmitted from a board inside the inverter through a serial port. In winter a partial shadow due to a chimney has been noted. PV field is composed by a unique string. The solution was adopted for a quick PV modules setting and to avoid to install an interfacing strings electric board. The production prevision is 2400 ÷ 2500 KWh/y which corresponds to 2,9 ÷ 3,0 heq.

Simulation. Data input. City: Udine; latitude: 46°; inclined roof plane: 20°; Azimuth: -5°; consumption energy in a year (KWh): 2500; yearly intensity radiation (KW m^2): 1339.

Data output. Electric energy convey on grid (efficiency 78% ÷ 82%): 1044 ÷ 1098 KWh/y; The power PV plant we should install will be: 2277 ÷ 3395 KW.

Valle di pesca Francamella Grado (Go): historically is the first private PV plant SA installed with public financing (22 December 2003). Drawn up by Ditta Pozzetto Silvio Impianti Elettrici sas Manzano (Ud) and carried out by Ditta Essedue sas of Sandrini Simone di Farra d'Isonzo (Go).

Plant charateristic, components and production results: a) 30° slope south oriented with a structure in steel inox dropped on a wood table; b) Ns = 9 strings with surface extension S = 22, 8 m^2; c) number modules Np = 14 model I165 165 Voc = 21, 6 V, Isc = 10,14 A, Ipm = 9, 48 A, Vpm = 17, 4 V monocrystalline Si; d) N. 1 inverter AJ2000 electric power line and N. 1 inverter AJ2400 on electric light line with a sinusoidal pure voltage until nominal power: 5 kW and 1 KW respectively; e) charge regulator 24V/30 A; f) Pb gel accumulator Nb = 12/2 V capacity 630 Ah.

Comment. PV plant is without monitoring system. The reason is that there is no explicit convenience to know the production because there no possibility to save money since the plant is electric grid less. Moreover this plant works at intervals when accumulators is discharged and so not all the power is utilized. To take advantage from this type of PV plant we should flow electric current in dead intervals (accumulators are fully charged but sun radiation strikes PV field) through a derivative branch. For example to supply electric energy to pumps to mix or to lift up water or to produce hydrogen in an electrolysis process.

Simulation. Unknown. A convenient software should be drawn to evaluate energy electric production in function of energy consumption.

AMGA Spa Società multiservizi (Udine): it is historically the first public PV plant GC built with 2001 financing of Environment Ministry and working from 24 April 2002. Drawn up and carried out by Ditta Gechelin Group Thiene (VI).

a) Terrace roof 20 m high from ground with modules fixed on metallic structure fixed on floor with a tilt of 30°; b) Ns = 6 strings on a surface of S = 180 m^2; c) number modules Np = 200 model PW1000 Ipm = 2,9 A, Vpm = 34,4 V, polycrystalline Si, d) N. 6 inverter SB3000 until a nominal power 3,0 kW AC side; e) on 31.12. 2004 the production was E = 54 243 Kwh.

Comment. Every inverter is a monophase electronic apparatus is joined to a single phase of a system three phase distribution. PV system is automatically monitored respect to these conventional quantities: kW, kWh, th, CO2; data are reported on a pc screen transmitted from *Data Logger* that collects data from 6 inverters; a peak power of 18,3 KW was found. Thanks to a download software it has been possible to read on a file displayed on excel a break of energy electric flux. Strings interrupted to push energy on grid from 13 to 14.09 2003 (ignored casualties) and the string WR30-002 from 25.02 2004 to 13.06 2004 because of a damage in an inverter. Nevertheless the inconvenience, on 31.12 2004 a production of 54 243 KWh was read. The effective production has been about 62700 KWh that corresponded to heq = 3,13. A good result but not the best, if we consider that azimuth and tilt have an optimum asset. A good "performance" should be 3,3 heq. This is an open question because is not clear if it is due to an inverter power limit or to an effective module power less than nominal power.

Simulation. Data input. City: Udine; latitude: 46°; inclined roof plane: 30°; Azimuth: 0°; consumption energy in a year (KWh): 23 000; yearly intensity radiation (KW m^2): 1371.

Data output. Electric energy conveyed on net (efficiency 78% ÷ 82%): 1069 ÷ 1124 KWh/y; The power PV plant we should install will be: 21 150 ÷ 20 463 KW.

Town Hall, Gymnasium, Middle school – Comune Montereale Valcellina (Pn). N. 3 PV plants GC by ENEL in October 2004.

N. 2 PV plants on slopes roof about 10° inclined and N. 1 PV plant 30° on a metallic structure (see photo N. 9). Every PV plant is composed with the same components: a) Ns = 2 strings with a surface on S = 23 m^2; b) number modules Np = 18 model I165 Ipm = 9, 48 A, Vpm = 17, 4 V in monocrystalline Si; c) N. 1 inverter Sunny Boy SB2500 until nominal power 3,0 kW.

Comment. Two PV plants, Town Hall and Middle School, are completed monitored with a Data Logger connected with an inverter (input) and synoptic panel (output). Data logger transmits to synoptic panel these conventional data: kW, kWh e CO2. Data logger has been provided with a serial port to transmit data to pc automatically restored in a data logger. In this way it is possible a complete monitoring of electric power compared with environment radiation (KW m^2) and temperature (°C).

Simulation. Foreseen.

Cervesato G. sas – Pradamano (Ud). PV plant GC by ENEL in September 2004.

a) Terrace roof inclined about 10° with PV field south oriented; b) Ns = 6 strings with a surface about S = 925 m^2; c) modules number Np = 144 model I65 W Ipm = 9, 48 A, Vpm = 17, 4 V monocrystalline Si; d) N. 1 inverter Sunway T up to 32 kW maximum power; e) total hours not available.

Comment. A single three phase inverter interfaced with a field electric board connects all the strings and conventional production data are displayed on a little synoptic panel in front of the unit door. No other data are available at present.

Simulation. Forseen.

7. Presentation of some results in PV production (open air results). The practical problem that initially inspired the present work of collection and elaboration of PV production data, was to study the conditions to overcome the testing of PV GC plants.

In the program "10000 Photovoltaic roofs", the MINAMB and Italian Regions have settled test conditions suggested by ENEA. At a first look they seem not restrictive: they establish a wide margin and it seems impossible not to overcome the test. But let us single out the arguments:

a) efficiency on direct current (DC) side must be greater than 0.85 (85%): we suppose power loss in a PV cells, in the contact areas, in the cables joining modules and strings to the inverter.

b) efficiency on alternating current (AC) side must be greater than 0.90 (90%): this power loss is inside the inverter due to warming in working condition.

c) total efficiency is the product of the two previous efficiencies: approximately 0.75 (75%).

The program "10000 Photovoltaic roofs", where we find technical supply characteristics to realize PV plants until 20 KW GC, include also formulae to calculate efficiency. They are expressed as follows:

$$Pcc > 0{,}85 * Pnom * I/Istc; \quad \Delta Pcc\% < 2\%$$

$$Pca > 0{,}75 * Pnom * I/Istc \quad \Delta Pca\% < 2\% \quad \Delta I\% < 3\%; \ (Wm^{-2}).$$

What is the reason that has inspired so wide margins of efficiency? Outdoor experiences reveal difficulties to pass a threshold test. Let us consider, in fact, ideal weather: steady meteorological conditions without moistness, calm wind, low air temperature, etc., and in STC (1000 Wm^{-2}, 25°). On the other side the PV cell tolerance certified in laboratory to define nominal power is not maintained in outdoor test; and furthermore there is no indication provided by manufacturers about the efficiency decrease after the first months of modules exposure at sun light. They have pointed out tests on different manufacturers' PV modules and they have turned out remarkable differences among the various amounts of nominal power after 3, 6 and 9 months[36].

Last but not least, efficiency decreases if temperature increases as we see at 3.2 sub paragraph. In the general rules that regulate 2001 announcement in Friuli Venezia Giulia Region there is a rule that permits to correct data in temperature over 25 °C. Graphs in following paragraph consider voltage and current coefficient variation over 25 °C: 2, 22 mV/°C and 17 $\mu A/c\ m^2$ °C.

The difficulties listed above influence also the efficiency measure of AC side, that is the inverter efficiency. For this unit, it is easily overcoming. In fact inverters manufacturers declare unanimous a high efficiency over 95%, while the minimum threshold is fixed in 90%.

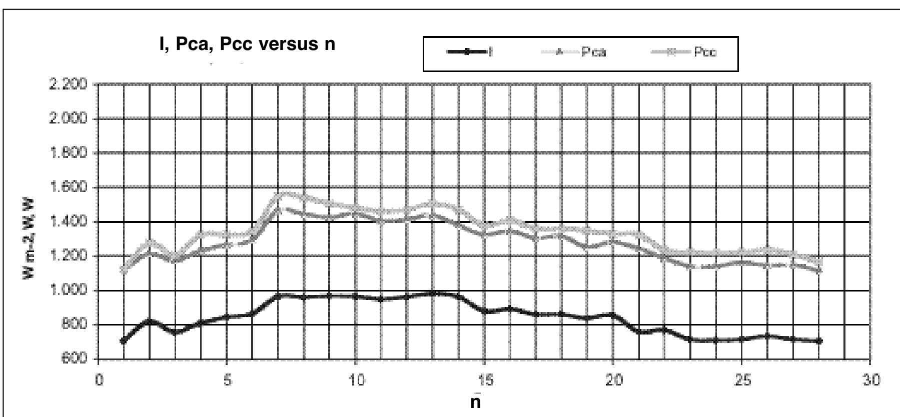
There is another threshold to take in account in a test measurements session. Intensity radiation must exceed 700 $W\ m\ m^{-2}$. We think that this threshold has been chosen because it has been observed, under it, a non linear function intensity light radiation/electric power.

In the next page productions will be presented and the outcomes in three small PV plants discussed. Let us proceed to analyse them in order from the date of production start. For each we have monitored production data from morning hours until afternoon hours in stable meteo conditions (or almost stable) with the aim to draw the correlation between characteristic quantities (V(V), I(A), Ir (W m^{-2}), T(K)) and the efficiency conversion. The efficiency tests requested by Regional Technical Services Board consider AC side data. The graphics compare CC side to AC side PV production, or the effective power on PV field, result different from PV nominal power for all the three PV plants. Moreover a correction in temperature has been also introduced for all the three PV plants.

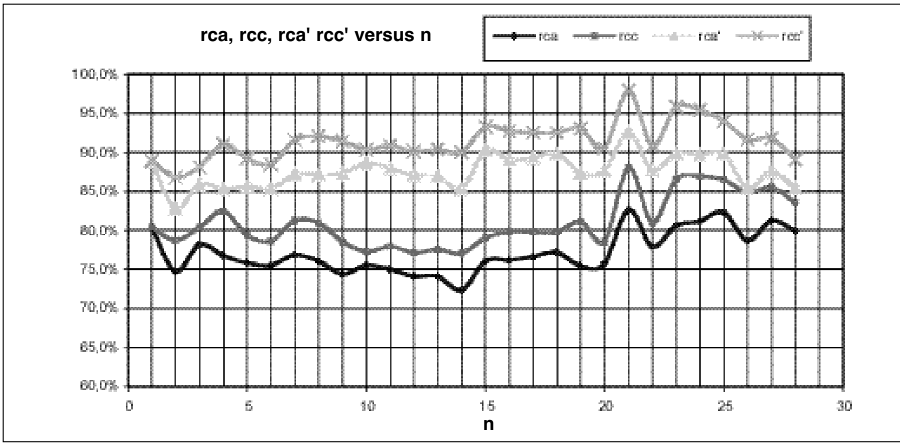
Notes about graphics

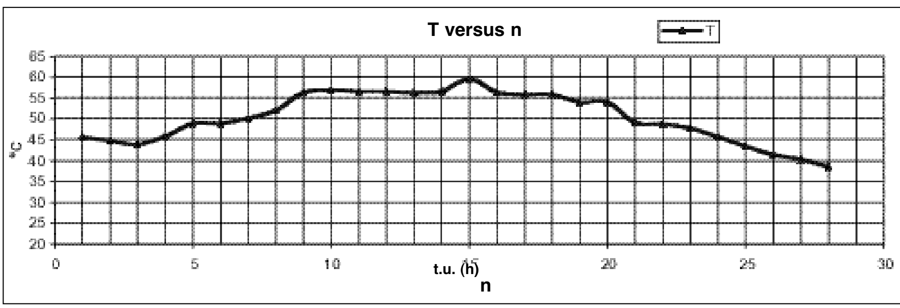
PV field efficient p.c. AC and CC side are calculated with:
rca% = I/1000. (Pac/Ppm). 100; rcc% = I/1000 (Pcc/Ppm). 100
n is the measurements number;
the time interval changes from 3 until 15 minutes.

Dalmasson L. house. The production data of this house has been read on the inverter display: kWh, W e CO2; instead, intensity radiation and temperature (W m^{-2}, °C) on a sun meter display (Photo 4.1).



- Data collected (day/interval time): 11.08. 2004 / 10h e 30m to 15h 30m;
- early and late in the morning, temporary clouds dimmed sun rays, in the rest of the day, bright sky;
- testing on AC side is on average overcoming in about 78,5% of the number of measurements;
- testing on DC side is on average

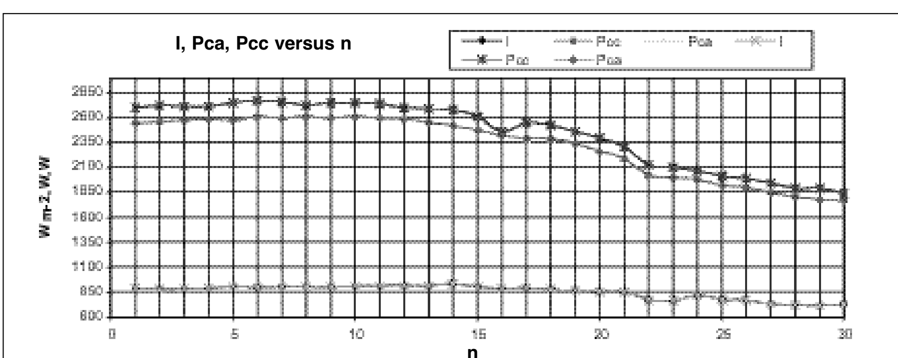


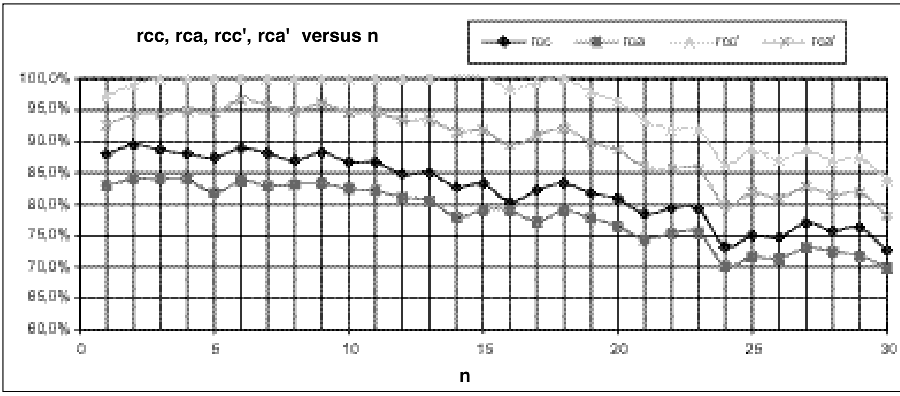


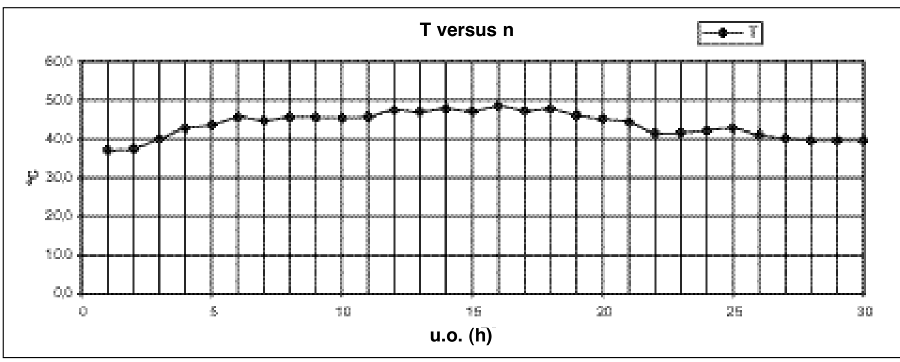
overcoming in about 18% of the number of measurements (in afternoon hours);

- testing on AC and DC side, corrected in temperature, are overcoming in 100%.

Cecotti S. house. Testing measurements methods have been similar to the previous case.

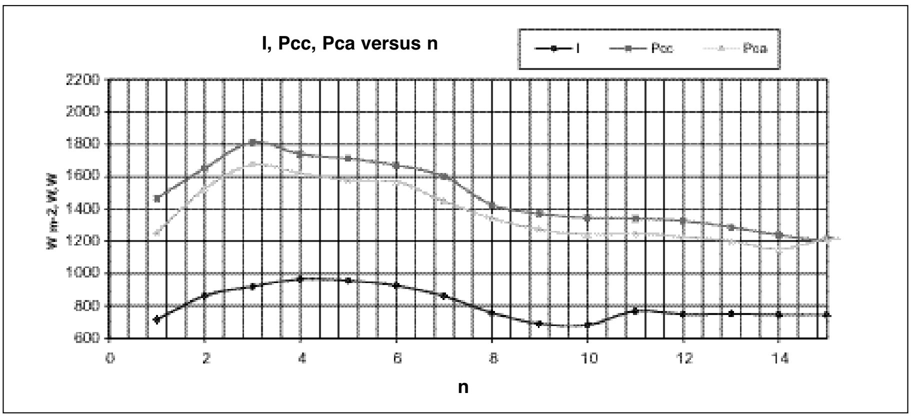


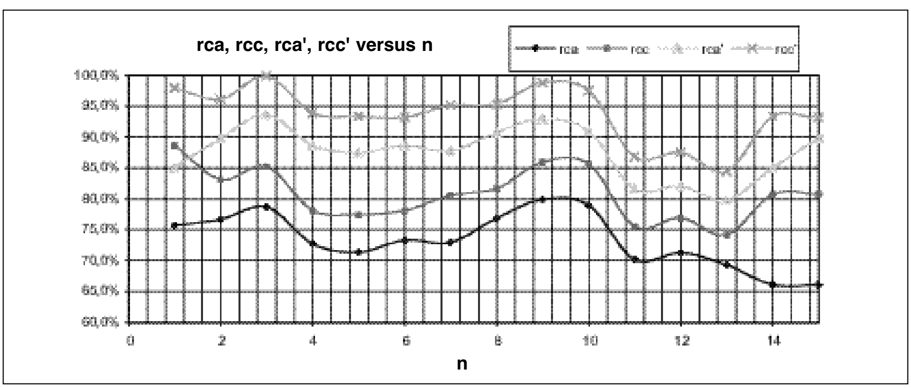


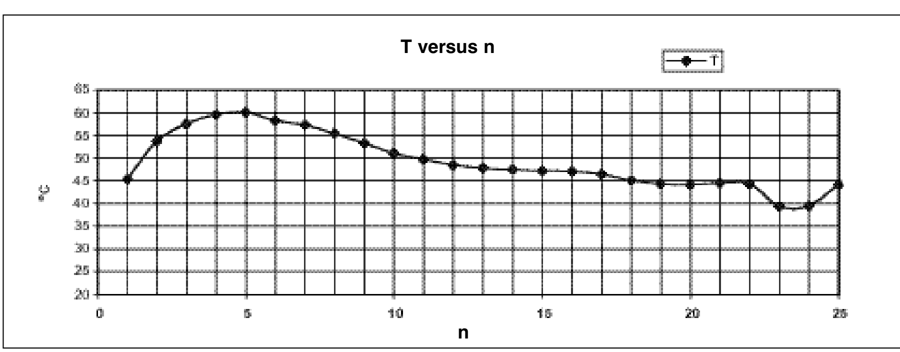


- Data collection are reported in two different days with meteorological condition similar: in the morning of 04.09. 2004 from 13h 25m to 16h 55m and in the afternoon on 06. 09. 2004 from 10h 15m to 13h 00m;
- similar meteorological conditions have characterized both days: bright sky but with blast of wind above all on 04.09. 2004;
- testing on AC side is on average overcoming in about 73,3% (almost all tests have not been overcome late in the afternoon);
- testing on DC side is on average overcoming in about 36,6% (almost all tests have been overcome early in the morning);
- testing on AC and DC side, corrected in temperature, are overcoming in 100%.

Pozzetto S. house. The production data of this house has been read on the synoptic pc desktop: kWh, W e CO2; instead, intensity radiation and temperature (W m^{-2}, °C) on a sun meter display.







- Data collected (day/interval time) 90.08. 2004/10h e 35m to 16h 10m;
- meteorological condition: bright sky and calm of wind;
  testing on AC side is on average overcoming in about in 24,0% (all test have been overcome in the early morning and in the last hour in the afternoon);
- testing on DC side is on average overcoming in about in 4,2% (a couple in the morning an a couple in the afternoon);
- testing on AC and DC side, corrected in temperature are overcoming on AC side for 52% and on DC side for 16%.

Conclusions. Even though the occasional nature of our research joined with a semi automatic measurement procedure and the few number of PV plants monitored (only three!) we can draw some conclusions.

In all three cases examined during monitoring operations, nominal power always has been lower than effective power. In the first PV plant (*Dalmasson L. PV roof*) the inverter has stored during its life time two data rather uncertain: 2010 W and 2100W that is over PV plant nominal power of 1980W... the data taken automatically shouldn't be as a gospel truth!

From this, a technical, economical question rises as regards the parameters to define the price in euros of PV watt. The manufacturer should at least indicate guaranteed minimum power for every module identified with a own serial number written on a back label of a module and should refer to this power for a real price euro/watt. Moreover also a name of the Laboratory and date where modules was been certified[37]. This last outcome is very important for an affordable business plan in order to account how many years are necessary to produce energy and recover the investment.

Otherwise there is no comparison among different modules and it is not possible to make homogeneous power strings to obtain maximum DC efficiency in a PV plant.

Finally the fundamental question of power correction in temperature. It's not easy to overcome the threshold of 75% (in effect a low value). This because the real power is distant from nominal power and also temperature. For high temperature is necessary to correct electric power in temperature. Not all data sheet modules reported coefficient to apply correction in temperature (see Table 3.1).

Moreover there are also physics aspects to consider for a deeper knowledge of this technology. For example it's not clear why polycrystalline Si is less effective in temperature than mocrystalline Si or also why Si poli crystalline is more efficient than Si mono crystalline when the surface is exposed to sunset light.

We have just touched the most important conclusions but to confirm them and study thoroughly this technology it is necessary to carry out a systematic evaluation of widespread monitoring while new plants will be installed. It's duty of regional Institutions, ENEA, Ministry of Environment to provide necessary means in order to plan such a research to improve knowledge for didactical training and estimate a more accurate prevision of PV technology profitability.

Actually this operation is on charge of the installers and data are verified by Regional Technical Service Offices. With the aim to make testing operation easy, the inverter should be connected with sensors of light and temperature. At present this apparatus, sensors and the electronic board, is not supported by public financing. In Italy ENEA is the referring institute supervising scientific activities and at present there is no scientific collaboration with Regional Technical Service Offices and ENEA in order to promote research in a institutional context, a clearly documentation and assistance to overcome difficulties and remove open questions to a more accurate economic evaluation .

Finally a hint to an extraordinary opportunity offered from INTERNET that public institutions should grasp: the possibility to connect inverter to a pc with an electronic card and a pc to internet. If all PV plants are connected, a network of a PV production could be monitored in real time. In this way they could evaluate the effective save energy programs sustained by public money on a large scale and also provide useful data for technicians and engineers.

8. Technical economic perspectives and policy to sustain PV technology diffusion. Nowadays it is a daily theme but for a long time neglected. Advantages and limits of public financing policy are well known. One of the most effective advantages has been to focus public opinion awareness on a local production of clean, renewable power by individuals and small communities to meet their own energy needs. Under this aspect, “alternative” to the fossil fuels traditional sources means to produce electric energy without the production greenhouse gases and not to substitute fossil fuels, at least in a middle period. The astonishing number of participants at public announcements in Italy, and in particularly in Friuli Venezia Giulia Region, marked a watershed between the present dominant “centralized” technology energy electric production and a “distributed” one. Fossil fuels will remain an important energy source for the next future, but they will eventually run out and the world will have to switch to an endless renewable power from sun. In this perspective silicon-based photovoltaic cell will have an important place. At present the principal problem is the PV cell cost that requires public investment for many years before becoming competitive compared with electric energy from traditional sources. In the meantime manufactures could find the way to produce PV cells more efficiently and also to drive down their high cost. Also important are the politics to promote renewable energy source. Under this aspect public financing policy have not been particularly fruitful. Main reasons are: a) inhomogeneous regional programs considered global financial amounts, the maximum admittable amount per KW and maximum percentage; b) complicated and not clear indications to prepare documentations without the help of experts; c) burocracy slowness practices to publicize beneficiary lists and to state accounts of completed PV plants; d) scarce efficiency from public main supply board (ENEL) to connect PV plants to the public grid; e) a maximum 20 KW PV plant limit, an investment not interesting enough for a private firm.

For all these reasons public Institutions are trying to find new financial tools to support PV plants with the aim to start a PV industry and train new professionals skills also in Italy. A promising financial tool is the so named "energy account". With this financial support the owner acquires a PV kit for the entire cost and then sells the electric production at a profitable price euro/KWh. In Italy, presently, a special law has been issued to rule the matter. Another incentive to install PV plants consists in the obligation for the main electric energy suppliers to issue "green certifications" which consist in the production of a quote of the total electric energy from renewable sources. This should also permit to acquire electric energy from PV plants owners associated in small communities. This last disposition is more directly joined to an international policy to reduce carbon dioxide (CO2) released by burning coal and gasoline for heat, electricity and transportation that are trapping excess energy from the sun (greenhouse gases).

But what we like to underline is that this plain record to have seen a little earlier and a little farther than others was born from a didactical event and a scientific passion. At the beginning of this work we have also mentioned that our association celebrated in 1999 the anniversary of Volta's discovery: the electric battery. Conferences and exhibits were organized with electric batteries on purpose built for the event, also in taverns and pubs in Udine. Without that "adventure" external to a didactical work in a classroom and its worries, there wouldn't have been any interest at school and inside the Institutions for this new field, no day and time dedicated to collect data, to elaborate, write papers with the only aim to improve teaching about renewable sources, researches and studies. Thanks to this event it has been possible to find convictions and support and to communicate the increased attention for this field with a participation at national AIF Congress and recently at SSTeF (Societât Sientifiche e Tecnologjiche Furlane) third Congress in Gorizia. I think this is one of the fields toward which to address our Region and Country, to raise the attention of entrepreneurs and remove fear for a tomorrow without development and innovation, above all thinking to young people this field promises interesting and stimulating perspectives: research, applications and economics results.

Thanks to: Pozzetto Silvio Electric Plants sas – in whose offices Giorgio Pozzetto, born into the profession, friend and colleague, has spent mainly his professional life. Pozzetto firm has carried out a pioneer function in the PV field

joining the realization of plants with studies, evaluations and support to research. A special care has been offered to me by AMGA Spa society and Angeli Bruno who welcome and took us to visit the plant and provided noticeable data and information to reflect on monitoring and collecting data, I could enjoy the nice helpfulness of the families: Dalmasson Luigino from Corno di Rosazzo, Cecotti Sergio from Cividale del Fiuli and Pozzetto Toso Gisella from Manzano. Thanks to their endeavour and braveness we could do experiences when we knew little about the perspectives and reliability of this technology. At school then, several times I met the colleague Paolo Modotto to discuss technical problems of electronic nature. I thank Silvano De Rivo of ITI “A. Malignani” who has built mechanical parts of the prototype “PV island” giving me priority in moments of discouragement. Components of gdl Agathos dell’ITI “A. Malignani” – Rolando Carmassi, Claudio Giusto, Giampiero De Marchi, Rodolfo Moro, Gildo Solari, and Giancarlo Toso – with whom I have spent a lot of time discussing about the project of Scientific and Technological Education (S&TE) for the production of prototypes to supply electric energy from renewable sources. At this point I feel the pleasure to address a mention to Paride Cargnelutti town councillor of Province Udine Education Board for the attention reserved to our aims, dott. Silvano Antonini Canterin and dott. Lionello D’Agostini President and Director of CRUP Foundation for financing support. I remind Cesare Silvi and Mario Gamberale of ISES in Rome that have provided the first news on public announcements and first indications on PV technologies since 1999, Carmine Quaglia of ENEA in Venice and Giorgio Treppo of CNA in Udine with whom I have cooperated to organize the first technical and practical lesson “open air” on PV plants in spaces near the gymnasium of ITI “A. Malignani”. The meeting with Alessandra Fornaci e Claudio Mitolo of ENEA gave me a big impulse with partecipation to the project “Sun at school”. During the workshop I was given the possibility to touch with hand the historical ENEA PV plants at Monteaquilone (Fg) and evaluate the results. Also people external to school have stimulated me. Humanly fruitful has been to know Maurizio Papetti at Enerpoint in Milan and Vanes Vitali of Elettronica Santerno in Imola (Bo) always kind and available to give me useful and precise indications on the characteristics of their products. Among the people in Friuli, I wish to emphasize the support of Masotti Mauro of Masotti Energy Service in Udine, a pioneer in the spreading of PV technology in Region and in Italy, Dario Giaiotti of OSMER – ARPA agency of Friuli Venezia Giulia Region which supplies meteorological data to ITI “A. Malignani”. Finally, as regards physics field, I consider a precious contribution the documentation sent me by Roberto Fieschi of Parma University, and the stimulating reflections with Lucio Fregonese from Pavia University about the origin of voltaic electric tensions. They are not properly technologists, but men of science and cognitive thoroughness, and gave me meanings to applications with their researches, and their scientific passion warmed and motivated me.

[1] In the letter, published al lot of months later in the *Philosophical transactions of the Royal Society of London* (Tomo XC, parte II, pag. 403 segg.) with this title *On the electricity excited by the mere contact of conducting substances of different kinds*, Volta announced to the world the discovery of electric battery (note from *Alessandro Volta* di G. Polvani, Domus Galileana, Pisa 1942 – XX reprint 1999, p. 340).

[2] E. Bequerel, *On electric effects under the influence of solar radiation*, Compt. Rend, 1839, vol. 9, p. 561.

[3] Is the famous third memory *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*, by A. Einstein published in *Annalen der Physik*, vol. 17, 1905, pp. 132-148: *On the heuristic point of view in light emission and transformation*.

[4] The diode is a special transistor, a ‘trans diode’, because the base and collector leads are joined together.
[5] Max Planck (Kiel 23/04/1858 – Göttingen 7/10/1947) stated for the first time the postulate of quantum energy, and the constant that derived from his name, on 14 December 1900 to the members of Deutsche Physicalische Gesellschaft in Berlin.
[6] It isn’t sufficient for pushing an “electric fluid” in a closed circuit to have contact between material surfaces chemically different, but it’s necessary to interface a humid conductor.
[7] We define *Fermi energy level* in a particular substance as the energy quantum state that has 50% probability to be occupied by a valence electron independently by temperature. The charge carriers, with energy level approximately near Fermi level, become free carriers if they have higher energy than the “energy gap”.
[8] The conduction in a silicon diode occurs at approximately 0,7 eV. In a forward bias and in a reverse bias the voltage is slightly greater and lower than 0,7 eV.
[9] The diode applications are very important in PV modules and in PV plants to block possible dangerous reverse electric currents in PV cells.
[10] At 25 °C the barrier potential in silicon is about Eg = 0.7 eV that corresponds to an approximate value of length wave μ.= 2.88 μm that falls in infrared field of the spectrum.
[11] In Si-n majority electrons and holes concentration is respectively: $n \approx 10^{17}$ and $p \approx 10^{4}$.
[12] For a wide look on PV technology state of art *Ilsoleatrecentossesantagradi*, N. 10, november 2004, p. 12 in www.isesitalia.it.
[13] At present PV cells production depends largely on electronic industry production wastes (electronic degree PV cells).
[14] Formula from Reprinted P. Rappaport, *The photovoltaic effect and its utilization,* p. 20 (see bibliography).
[15] The value: $k = 3.80\ 10^{-23}\ jK^{-1}$.
[16] The electron charge value $e = 1.60\ 10^{-19}$ C.
[17] Shockley equation in scientific literature.
[18] In STC the intensity solar radiation is 1000 (Wm^{-2}), air mass AM is 1.5 and cell temperature is 25 °C.
[19] In PV plants connected to a public grid (ENEL in Italy) the automatic electric load assessment is made by the apparatus (inverter) that converts DC PV plant electric energy into AC public grid electric energy.
[20] Testing rules in PV plants prescribe a minimum PV module efficiency conversion of 85% with intensity radiation higher than 700 W m^{-2}.
[21] This note considers electric energy stored in electric accumulators in stand alone PV plants energy production.
[22] Here some data from three manufacturers sources: 1) Pmp = 165W: -2,2mV/°C on Voc and +0,017mA/cm^{2}°C on Isc; 2) Pmp 158W: -0,348mV/°C on Voc and +0,057mA/cm^{2}°C on Isc (-0,004mA/cm^{2}° C on Ipm e -0,474mV/°C on Vpm) 3) 105W: -0,38%/°C on Voc and +0,10%/°C on Isc.
[23] See “10000 FV roofs” announcement promoted by Udine Province in collaboration with MINAMB.
[24] The sun, in outer space at AM0 condition, is considered approximately a natural black body.
[25] The ARPA – OSMER Data Base is sent on the agathos@malignani.ud.it thanks to dott. Dario Giaiotti ARPA – OSMER Visco (Ud).
[26] A topic “Dalla scoperta della pila elettrica alla legge di Ohm. Exhibit interattivo di storia, scienza e tecnologia” has been presented on XXXIX Congresso AIF Milazzo (also see bibliography).
[27] The programmable controller utilized has been a Kloeckner Moeller model PS3.
[28] Sun tracking need two axis: a daily tracking the one and a season tracking the other.
[29] First PV market was the outermost space. First artificial satellite with PV cells on board was fired on 17 March 1958, Saint Patrick day. This performance was the outcome of a USA Vanguard military programme. Subsequently PV plants were installed on Exxon oil platforms in gulf of Mexico (...what ironic destiny!).
[30] The short term SA, from the initial letters of *Stand Alone*, is more commonly used in technical literature.
[31] This type of PV plant is pointed with the acronymous GC from the initial letters of *Grid Connected.*
[32] For this plant the acronym is a combination of the previous: GC-SA.
[33] $\Delta Voc = Voc\ max - Voc\ min$
[34] Data reported are updated on the day of the writer’s lecture on 16 October 2001, III Congress SSTeF Museum Hall in Gorizia Castle.
[35] The sun meter implied was SLM018C Mac Solar.
[36] *Qualità e resa energetica di moduli FV – Centro di Ricerca LEE – TISO*, FV periodic *L’elettricità dal sole*, anno 1, 2 / aprile - giugno 2004.
[37] Rules are CEI/IEC 61215.

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