INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.704 - 38

Workshop on Materials Science and Physics of Non-Conventional Energy Sources

(30 August - 17 September 1993)

"Electricity Production by the P.V. Source and "Overview of the ENEL Activities in Renewable Energies"

A. Previ
ENEL
via Alessandro Volta 1
Cologno Monzese (Milano)
Italy

These are preliminary lecture notes, intended only for distribution to participants.

DETERMINATION OF OPTIMUM TILT ANGLE OF PANELS IN LARGE SCALE PHOTOVOLTAIC ARRAYS

A. Iliceto (*), A. Previ (*), G. Chimento (**), S. Guastella (**)

(*) ENEL-DSR-CREL
Via A. Volta, 1
20093 Cologno Monzese (MI)
Italy
Tel. +39-2-88471
Fax +39-2-88475465

(**) CONPHOEBUS Scrl
Zona industriale Casella postale
95030 Piano d'Arci (CT)
Italy
Tel. +39-95-291407
Fax +39-95-291246

ABSTRACT - To determine the optimum tilt angle of panels in large scale flat-plate photovoltaic arrays both theoretical and experimental activities have been carried out. A theoretical method to determine the solar radiation collected by PV arrays which considers meteorological data, module glass reflectivity and array type (single or multiple rows) was used. This method has been implemented as compared with others in order to consider the accumulation of atmospheric pollution on panels. An experimental activity consisting of measurements of glass reflectivity and atmospheric pollution accumulation on panels have been carried out in Conphoebus test facilities. One year data of continuous operation of 4 flat-plate arrays, south-facing and differently tilted, in ENEL's PV test field at Adrano have been used to analyze the accuracy of the method. Using this method the determination of solar radiation collected by a large scale PV array sited in Southern Italy has been made and relevant indications according to the optimal tilt angle of the array have been given.

1. INTRODUCTION

Determination of solar radiation available on differently oriented surfaces is required in PV array design. Usually, in Northern hemisphere, the arrays are oriented towards south to maximize the produced energy over an entire day. Moreover the tilt angle is chosen taking into account the necessity to maximize the produced energy, over an entire year or over the season in which the load energy demand is greater. When choosing the array tilt angle, it must also be taken into consideration that low tilt angles involve simpler and more economic panel supporting structure, smaller land area but more dust accumulation because of atmospheric pollution on module glasses.

The larger the PV array is, the more important the choice of the optimal azimuth and tilt array angles is.

2. A PROPOSED METHOD TO DETERMINE THE SOLAR RADIATION COLLECTED BY LARGE SCALE PV ARRAYS

To determine the solar radiation incident on a tilted surface many theoretical methods, which consider meteorological data, are available /1, 2, 3, 4, 5/.

In order to obtain a better accuracy when determining the solar radiation collected by large scale PV arrays, an improved method has been developed, which takes into account some particular effects.

2.1 Effects to be considered for the determination of the solar radiation collected by large scale PV arrays

a) Module glass reflectivity effect

When the solar beam reaches PV module glass, it is partly reflected and partly transmitted into the module. The glass reflectivity (i.e. the ratio of the irradiance reflected by a specific surface to the irradiance incident upon it) is a function of the incidence angle and of the refraction coefficient of the air-glass interface. Measurements of module glass reflectivity have been carried out in Conphoebus test facilities: I-V characteristics of a differently tilted module have been taken by means of a pulsed sun simulator. The following results point out the glass reflectivity effects:

1) module glass optical transmittance decreases when the incidence angle of solar radiation increases; measurements show that transmittance decreases especially with an incidence angle over 50° (see Fig. 1);
2) power generated by the module is lower than could be expected if just the cosine law is considered (see Fig. 2).

b) PV array type effect

The collected solar radiation changes according to the type of PV array: single or multi-row. In the case of multi-row arrays, each row can be shadowed by the front row decreasing collected solar radiation.

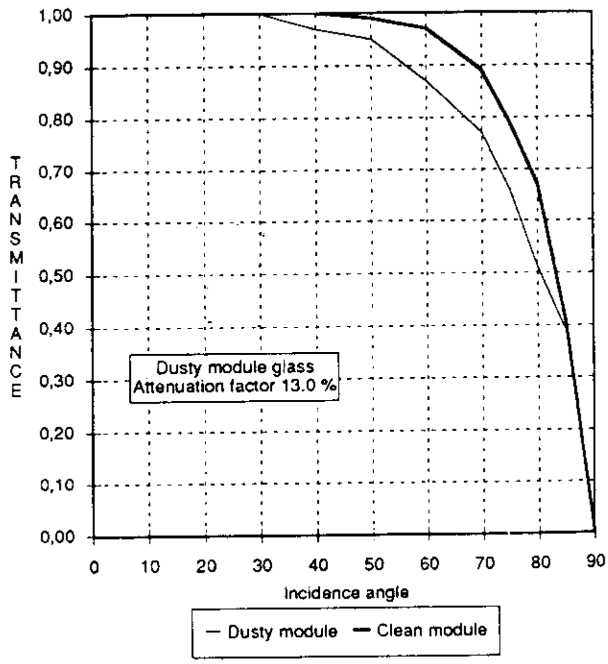

Fig. 1 - Glass optical transmittance versus incidence angle of solar irradiance on clean and dusty modules. Measurements made by means of pulsed sun simulator.

c) Atmospheric pollution accumulation effect

If low tilt angle of panels is chosen, the effect of atmospheric pollution accumulation on PV module glasses becomes particularly important. Measurements of dust accumulation have been carried out in Conphoebus test facilities: differently tilted single modules (0°, 10°, 30° and 60°) have been exposed outside and module glasses have been cleaned off only by meteorological events. During one year monthly measurements of module I-V characteristics at Standard test conditions have been taken. The following results point out the dust accumulation effects:

1) the module output power decreases when the dust accumulation level increases, according to the module tilt angle and the meteorological conditions (see Figures 3 and 4). One year outdoor exposure has produced, on PV modules, an average decrease in generated power, in comparison with the initial values. This was as high as 4.4% (with maximum value of 13%) for horizontal module, against an average of 2.9% for

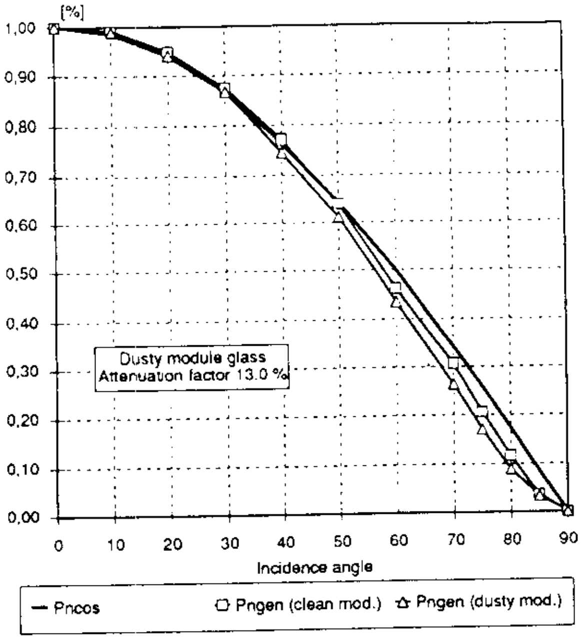

Fig. 2 - Decrease of generated power versus incidence angle of solar irradiance on clean and dusty modules. Measurements made by means of pulsed sun simulator.

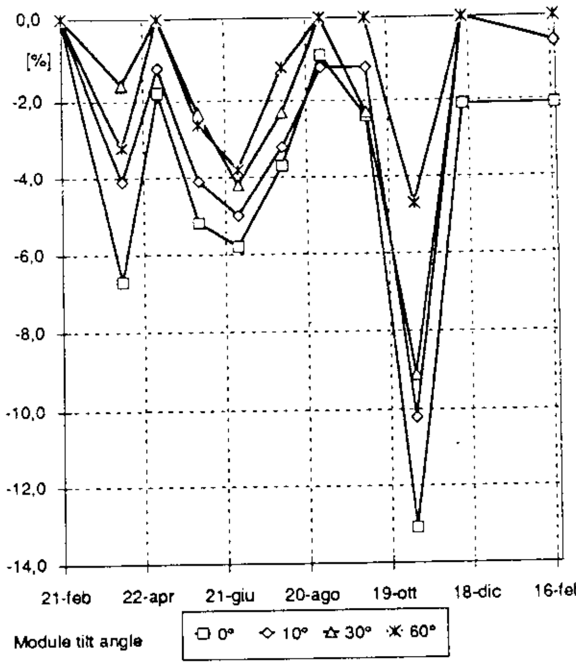

Fig. 3 - Effect of dust accumulation on differently tilted (0°, 10°, 30° and 60°) single PV modules at Conphoebus test facilities (Catania, Italy, 1989-90). Monthly differences with respect to the initial measured power.

the 10° tilted module, 2.1% for the 30° tilted one and 1.8% for the 60° tilted one;

2) the module glass optical transmittance, with respect to the incidence angle of solar radiation, changes as the dust accumulation level on the module does (see Fig. 1); measurements show that dust accumulation emphasizes transmittance decrease especially when the incidence angle is over 50°.

These results could depend on site, meteorological conditions and type of module glasses; therefore the values obtained by measurements cannot be assumed as always valid. Nevertheless, they allow an evaluation of the influence of the aforementioned parameters on the solar radiation collected by differently tilted large scale arrays.

2.2 Description of the proposed method

In order to obtain a higher accuracy in the determination of solar energy collected by large scale PV arrays, the proposed method takes into account the aforementioned effects.

a) Since the direct, diffuse and ground-reflected components of solar irradiance are differently reflected by glass, the determination of their reflection needs separate calculations /6/:
   - reflection of the direct component is calculated computing the incidence angle on an hourly basis;
   - reflection of the diffuse component should be calculated by integrating the reflectivity, as a function of incidence angle, over the part of sky seen by the module; the analytical integration can be avoided by considering the reflectivity as a constant (equal to its value when the incidence angle is 0°) and by decreasing properly the angle through which the sky is seen by the module;
   - reflection of the ground-reflected component is calculated in a similar way as diffuse component calculation.

b) The PV array type effect has to be considered /6/, taking into account that in the case of multi-row arrays: - the ground-reflected radiation can be neglected; - the diffuse radiation must be decreased by the same proportion of the part of sky shadowed by the front row; - the direct radiation does not change specifically because usually the distance between two rows does not allows any shadowing during high radiation hours.

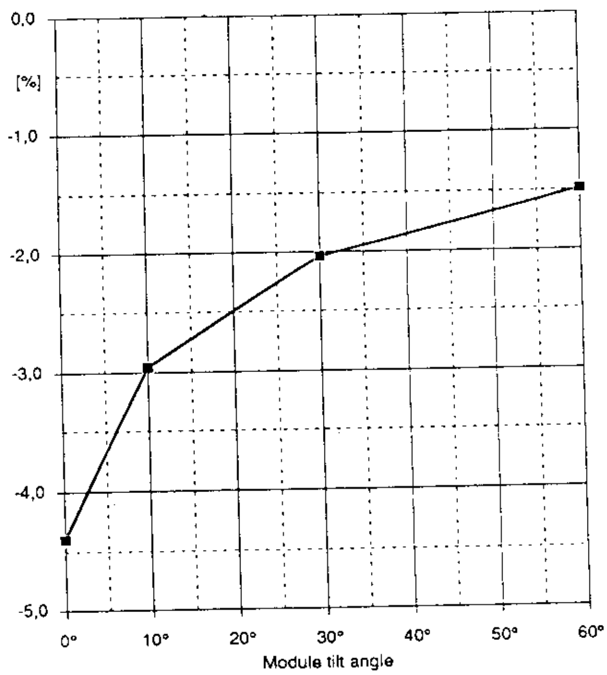

Fig. 4 - Effect of dust accumulation on differently tilted (0°, 10°, 30° and 60°) single PV modules at Conphoebus test facilities (Catania, Italy, 1989-90). Yearly average differences with respect to the initial measured power.

c) Finally, the effect of atmospheric pollution accumulation on PV module glasses has to be considered by adopting an attenuation factor for the collected solar radiation. This factor has to be changed with module tilt angle, according to the experimental data of dust accumulation on module glasses where yearly average values have been taken into account (see fig. 4).

2.3 Experimental data used to analyze the accuracy of the proposed method

To obtain an experimental determination of solar radiation collected by differently tilted PV arrays, more than one year operation of a PV plant, sited at Adrano (Sicily), has been monitored.

The Adrano PV plant is a test installation for photovoltaic generators, set up by ENEL and supported by EEC-DG XII. It consists of four 2.5-3 kWp flat-plate PV arrays connected by means of MPPT inverters to the local 20 kV grid /7/.

At the start of the activity PV arrays were cleaned off and set up south-facing and differently tilted (0°, 10°, 30° and 60°). During operation, the arrays were forced to work at their maximum power point by means of the MPPT's and the modules were cleaned off only by the whether events.

Available data, collected by a high-precision data acquisition system and off-line processed, allow the following considerations:

1) the 30° tilted array has produced 21% more energy than the horizontal one, the 60° tilted one 14% more and the 10° tilted one 11% more (see Fig. 5 and Tab. 1);
2) atmospheric conditions did not succeed in the complete cleaning of module glasses and after one year operation deposition of atmospheric pollution was evident, especially on the horizontal array.

In order to analyze the predictions of the proposed method the experimental data have been compared with the calculated ones. The collected solar radiation on differently tilted planes have been calculated starting from the daily radiation data monitored on the horizontal plane of the same site from March 1989 to April 1990 (see Tab. 1). The results of the comparison show that the prediction of collected solar radiation is quite more accurate when the reflectivity and dust accumulation effects have been considered.

3. PREDICTION OF SOLAR RADIATION COLLECTED BY A LARGE SCALE PV ARRAY SITED IN SOUTHERN ITALY

Prediction of solar radiation collected by a large scale PV array has been obtained (see Tab. 2 and Fig. 6), using the proposed method and the solar radiation data of the meteorological station nearer to the installation site of ENEL 3.3MW PV plant. Daily radiation data of the average year of the Naples station /8/ have been used.

In particular, for a large scale flat-plate PV array sited in this region, the following considerations can be made:

a) the optimum array tilt angle is near to 30° for the single-row array type and 25° for the multi-row array type (either if dust accumulation on glass is considered or not); nevertheless, even if the tilt angle varies between 15° and 35°, the annual solar radiation collected by a large scale PV array remains nearly constant (see Fig. 6). Appreciable losses occur at 10° (4% decrease of solar radiation collected using optimum tilt angle) and at 45° (5% decrease);
b) a single-row array, adopting the optimum tilt angle, collects during one year 9% or 12% less solar radiation than a horizontal multi-row array, according to whether the effect of dust accumulation on module glass is considered or not;
c) the use of a single-row PV array needs less land area than the multi-row one: the land area is a function of the tilt angle (-50% at 40° for single-row respect to multi-row; -36% at 20°; -23% at 10°); nevertheless, in a single-row array, a very low tilt angle is preferred or required in order to have a simple and economic supporting structure and to allow easy module inspection and maintenance, but this implies a relevant loss in the energy collected.

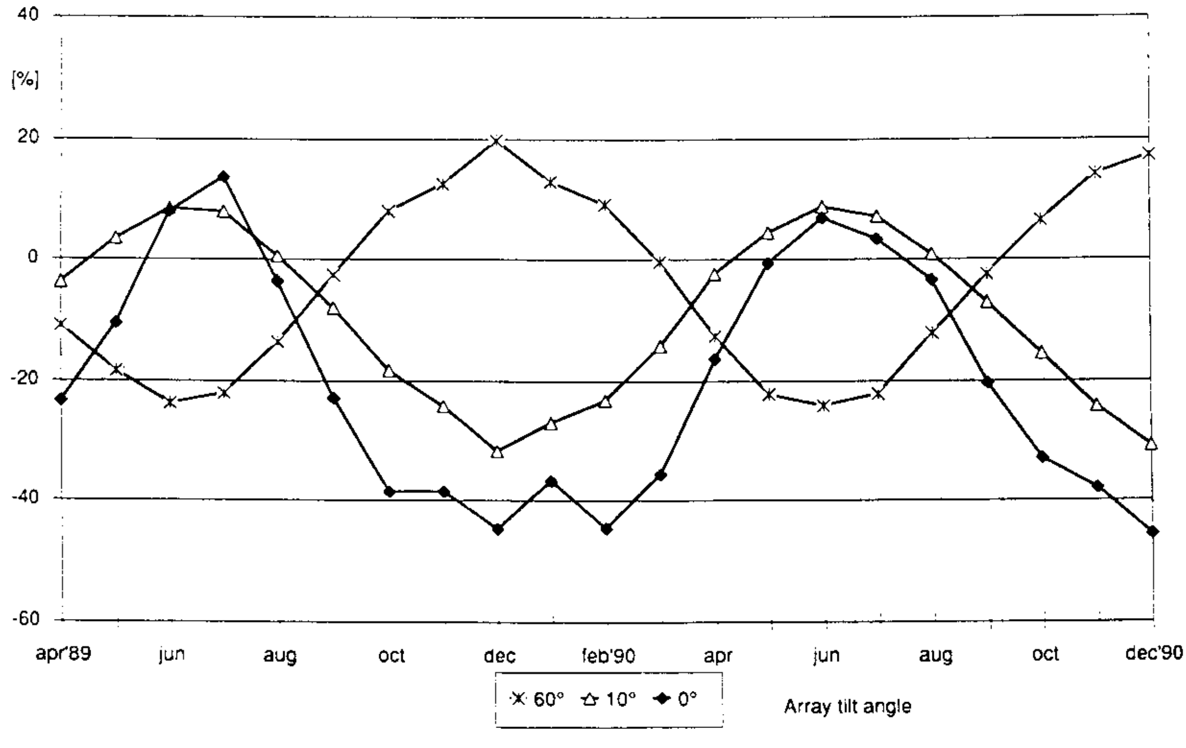

Fig. 5 - Adrano PV plant - Produced energy of 4 flat-plate arrays, south-facing and differently tilted: differences with respect to the 30° tilted array.

4. CONCLUSIONS

The processing of theoretical and experimental data shows that the proposed method allows the determination of the solar radiation collected by differently tilted flat-plate large scale PV arrays, taking into account meteorological data, module glass reflectivity, array type and accumulation of atmospheric pollution on panels, with sufficient accuracy for array design.

In Southern Italy (35 to 40° N latitude), the annual solar radiation collected by a multi-row South-facing PV array is quite constant changing its tilt angle from 20° to 35° with respect to the horizontal; setting up the panels on the horizontal plane, the annual solar radiation collection decreases of 12% considering also dust accumulation on panels. These considerations have led ENEL to the choice of a tilted multi-row array tilt angle of 20° for the 3.3MW PV plant to be sited near Naples. This choice is a good compromise between irradiance collection optimum tilt, low land occupation and simple array supporting structure.

REFERENCES

/1/ B. Y. Liu and R. C. Jordan - The interrelationship and characteristic distribution of direct, diffuse and total solar radiation - Solar Energy, Vol. 4, 1960

/2/ J. K. Page - The estimation of monthly mean values of daily total short wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40° N - 40° S - Conference on new sources of Energy, Rome 1961

/3/ S. A. Klein - Calculation of monthly average insolation on tilted surfaces - Solar Energy, Vol. 19, 1977

/4/ T. M. Klucher - Evaluation of models to predict insolation on tilted surfaces - Solar Energy, Vol. 23, 1979

/5/ J. K. Page and R. J. Flynn - The development of a meteorologically validated model for the prediction of inclined surface irradiation for the EEC area - Solar World Forum, International Solar Energy Society Conference, Brighton, 1981

/6/ F. P. Califano, V. Silvestrini, G. Vitale - La progettazione di sistemi fotovoltaici - Liguori Editore, 1988

/7/ A. Iliceto - The Adrano project - International journal of Solar Energy, Vol. 3, 1985

/8/ CNR - Dati climatici per la progettazione edile ed impiantistica - PFE February 1982

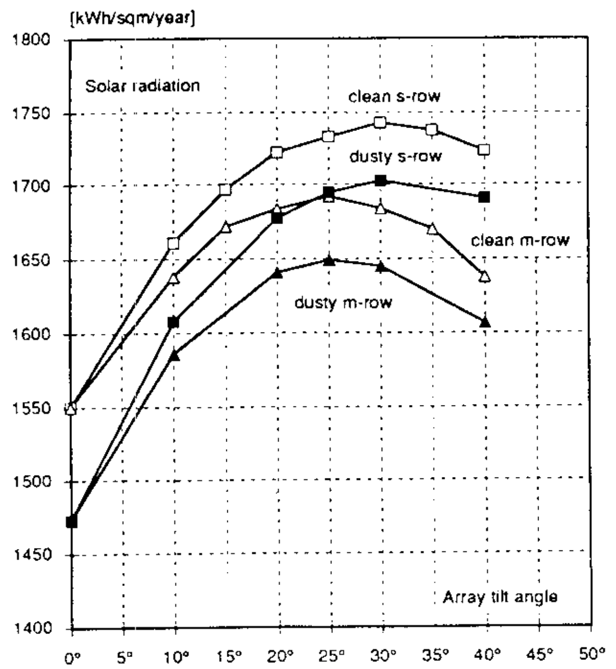

Fig. 6 - Yearly solar radiation collected by PV arrays versus array tilt angle in Naples region. Prediction obtained taking into account the effects of module glass reflectivity, array type and atmospheric pollution deposition on module glasses.

Tab. 1 - Comparison between predicted and measured solar radiation collected by differently tilted flat-plate PV arrays.
(Site ADRANO, lat. 37.30°N, Solar radiation data source: DAS ENEL/CREL, Mar '89 - Apr '90)

		Solar radiation data (calcul.)	Solar rad. data + reflectivity + dust accum. (calculated)	Operating data of 4 PV arrays (measur.)
Optimum array tilt angle		30°	30°	30°
Differences with respect to the optimum tilt angle [%]				
Adopted tilt angle	0°	-11.9	-14.9	-17.1
	10°	-5.9	-6.5	-8.2
	60°	-7.4	-8.7	-9.2

Tab. 2 - Prediction of yearly solar radiation collected by differently tilted flat-plate PV arrays.
(Site NAPLES, lat. 40.51°N, Solar radiation data source: CNR - IFA, average year)

		Solar radiation data	Solar rad. data + reflectivity	Solar rad. data + reflectivity + dust accum.
Optimum tilt angle		25°	25°	25°
Differences respect to the optimum tilt angle [%]				
Adopted tilt angle	0°	-8.5	-8.9	-11.5
	10°	-3.3	-3.5	-4.4
	20°	-0.5	-0.5	-1.1
	45°	-4.6	-4.7	-4.8
	60°	-13.4	-14.0	-14.5

ACKNOWLEDGEMENTS

The authors wish to thank Mr. A. Pappalardo (Conphoebus) for his co-operation in the management of Adrano PV plant and Mr. V. Piazza (ENEL-CREL) for the data processing of Adrano PV plant.

ENEL's 3-MW PV POWER STATION PRELIMINARY DESIGN

C.Corvi*, R.Vigotti*, A.Iliceto** and A.Previ**

* ENEL - DSR - Roma, Italy
** ENEL - DSR - CREl - Cologno Monzese (Milano), Italy

ABSTRACT. In the context of the Italian National Energy Plan, ENEL, the Electricity Authority, is developing a first utility scale PV generation plant, to be located in the region of Naples.
This paper presents the main technical characteristics of the plant at its preliminary design phase, and the available information of the principal components.

1. INTRODUCTION

The design of a grid-connected photovoltaic power plant is basically quite simple. It involves setting up a d.c. generator of a given size and power, coupled to a d.c. - a.c. static converter. However, the transition from the theoretical design to its implementation in practice involves a series of technical problems that are not always easy to solve and are not catered for by conventional plant engineering. The salient feature and the weakest point in photovoltaic conversion is, as it is known, the low degree of conversion efficiency of present-day photovoltaic modules. This aspect, which has only a slight bearing on the designing of small photovoltaic plants, becomes decisive when it comes to setting up power plants of MW dimensions.
The considerable amount of land required for such plants means the designer has some new and unusual structural and architectural problems to deal with. The possible solutions are many, but their effect on the cost of the system is significant. Moreover, low conversion efficiency also affects the electrical design of the project, inasmuch as setting up large power generators involves handling, assembling, and wiring tens of thousands of modules, which obviously means high labour costs.
By setting up this photovoltaic power plant, ENEL aims above all to ascertain the present costs of implementation and to improve design criteria, as well as the costs of future projects, so as to make them as competitive as possible compared to conventional power plants.
Let us now take a closer look at the design criteria applied.

2. DESIGN PARAMETERS

The designing of a grid-connected plant calls for knowledge of the main meteorological data in respect of the site under consideration (i. e., solar energy, temperature, wind speed). The system has to be so designed that it will guarantee a given annual production of electric energy and peak power throught the year.
The design parameters to be defined are:
- The tilt angle
- The system's conversion efficiency.

Both the above quantities have to be laid down so as to ensure that the maximum energy is produced for a given amount of installed generating power.
Various more or less sophisticated methods can be used to calculate the optimal tilt angle. In the case of the plant in question, use has been made of the methodology indicated in (1).
The chosen value of 20° is based not only on energy, but also on practical considerations, as follows:

- Module self-washability
- Reduction of the area taken up by the plant
- The possibility of supplying only slightly below rated installed peak power in winter time.

As regards the electrical efficiency of the system, (ratio between the DC and the AC rating) the aim has been to obtain the best, compatible with a number of constraints, imposed both by the current state of the art in respect of photovoltaic modules and by Italian safety regulations. The first step to reduce the ohmic losses of the array, given the same power output, it's to fix the rated voltage as high as possible. In the case of photovoltaic plants, there are practical limitations on the use of high voltages for the following reasons:

- The output voltage from the plant depends on the number of modules arranged in series; it has been estimated that when the number of modules connected in series exceeds a hundred, the reliability of the system begins to diminuish (2).
- If the plant's voltage exceeds 600 V, steps have to be taken, in accordance with Italian safety regulations, to isolate the plant from the public and also from maintenance staff.

For all the reasons mentioned, the operating voltage of ENEL's plant has been fixed at 330 V (i.e., about 400 V no-load), thus allowing

reliability and safety margins.
Again in order to keep electrical losses of the d.c. generator within bounds, it has been decided that all wiring be designed not to exceed a current density of about $1A/mm^2$, at peak power.
In addition to ohmic losses, photovoltaic generators suffer internal losses due to the lack of homogeneity in the electrical characteristics of the numerous photovoltaic modules of which they are made up. More or less complicated criteria to optimize the matching of modules in series and in parallel can be adapted (3). The basic principle is to connect in series the modules that supply very similar currents, and in parallel the modules or strings of modules that have very similar voltages. In this case, too, practical considerations have meant that modules are classified and subdivided as little as possible, in order to complicate on-site assembly as little as possible. In the case of the ENEL plant, the modules will be subdivided into two current and voltage classes balancing cost of installation and array efficiency.

3. ELECTRICAL DIAGRAM OF THE PLANT

Particular attention has been paid to the electrical layout. First of all, the 3-MW power plant has been subdivided into 10 sub-field, each with a gross power of 330 kW peak. Each sub-fields is electrically independent of the next, since it is connected to the 20-kV network by means of its own converter. All the sub-arrays therefore operate electrically in parallel on a buried 20-kV loop running throughout the area of the photovoltaic plant.
Each sub-array is broken down into two galvanically separate sections, and is connected to the converter in accordance with the diagram in Fig.1.b.
This 4-wire layout is functionally identical to the 3-wire system with the center tapped to ground, as described in Fig.1a.
Of the two alternatives, the choice fell on that in Fig. 1b, which offers the advantage of operating as a floating photovoltaic plant, isolated from the ground. The main plus point here consists in the fact that ground fault causes the circulation of only very weak fault current.

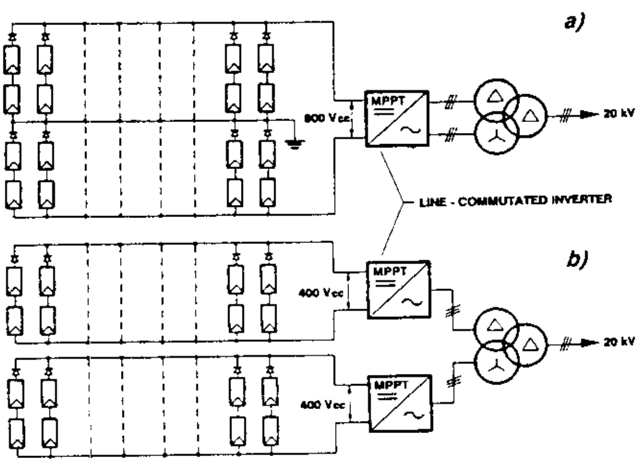

Fig. 1. 3MWp PV power plant - Possible electric lay-outs of one sub-field (330 kWp)

4. PHOTOVOLTAIC MODULES AND SOURCE CIRCUITS

The ENEL photovoltaic plant will be equipped with polycristalline silicon modules. During 1990, both Italian and non-Italian manufacturers were invited to submit tenders for the supply of the 10 sub-arrays into which the plant is subdivided.
The electrical diagram proposed by ENEL provides for a 72 cell module with a power of about 90÷100 Wp and a voltage at maximum power of about 17 V d.c. The diagram is given in Fig. 2b. The module is twice the size of the 36-cell type available on the market. Obviously, the 72-cell module has the following advantages over the smaller kind:

- Higher power density (W/m^2), given the same cell output.
- Saving in material
- Only half the amount of work required for assembly and wiring of the modules.

Some of the manufactures approached stated they were prepared to supply modules with the characteristics indicated by ENEL, while others were prepared to provide either 36-cell or 72-cell modules, but with twice the output voltage required (i.e., 35 V d.c.).
Consequently, assuming all the sub-arrays operate at the same voltage of 330 V d.c., there will be sub-arrays with source circuits consisting of 20 or 10 modules connected in series of the large type, and sub-arrays with 20 module strings in series of the small type.

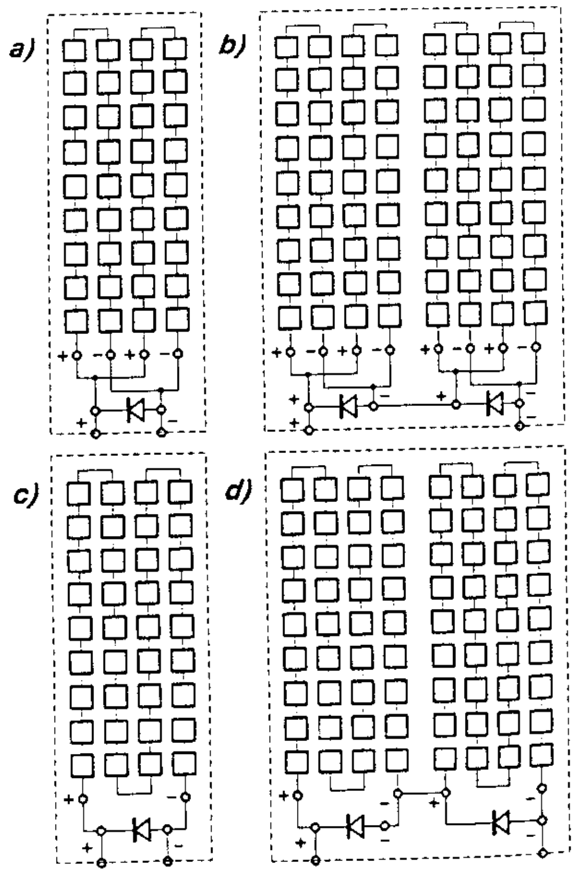

Fig. 2. 3MWp PV power plant - Electric lay-outs of the pv modules to be installed

5. ENERGY CONVERSION

The energy generated by each sub-array will be converted into a.c. and stepped up to medium voltage (20 kV) by means of a line-commutated inverter and a step-up transformer. The inverter consists of two three-phase bridges connected to the two secondary windings of the step-up trasformer, as show in Fig. 3. The targetted efficiency of each converter is 92% at full load. Each bridge is equipped with MPPT control logic. This logic, developed by ENEL (4) makes possible maximum feed into the network of the power generated by the sub-arrays. In one of the sub-arrays, it is planned to install a further forced-commuted inverter, to operate alternately with the line-commuted one. This unit, which will also have an MPPT circuit, is an experimental prototype.

6. INTERFACE OF THE SUB-ARRAY WITH THE MEDIUM-VOLTAGE NETWORK

All the sub-arrays will be supplying the energy produced in the 20-kV network.
A special, buried loop-line therefore runs throughout the central area, linking in parallel the primary windings of the step-up transformers of the static converters (see Fig. 4). At the interface with the network, suitable filters to compensate for the harmonics and banks of capacitors for power factor control will be installed.

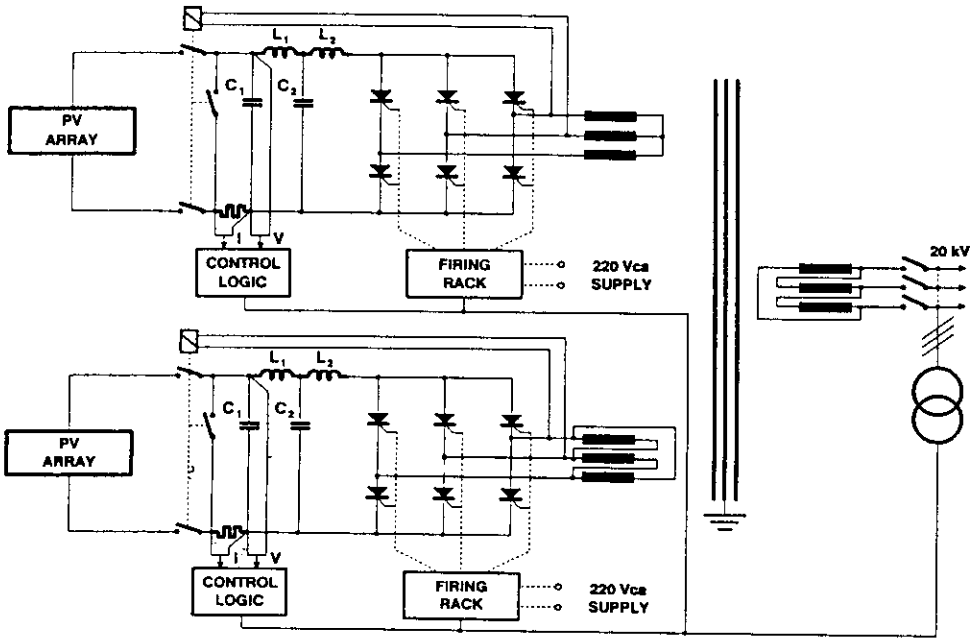

Fig. 3. 3MWp PV power plant - Lay-out of the converters

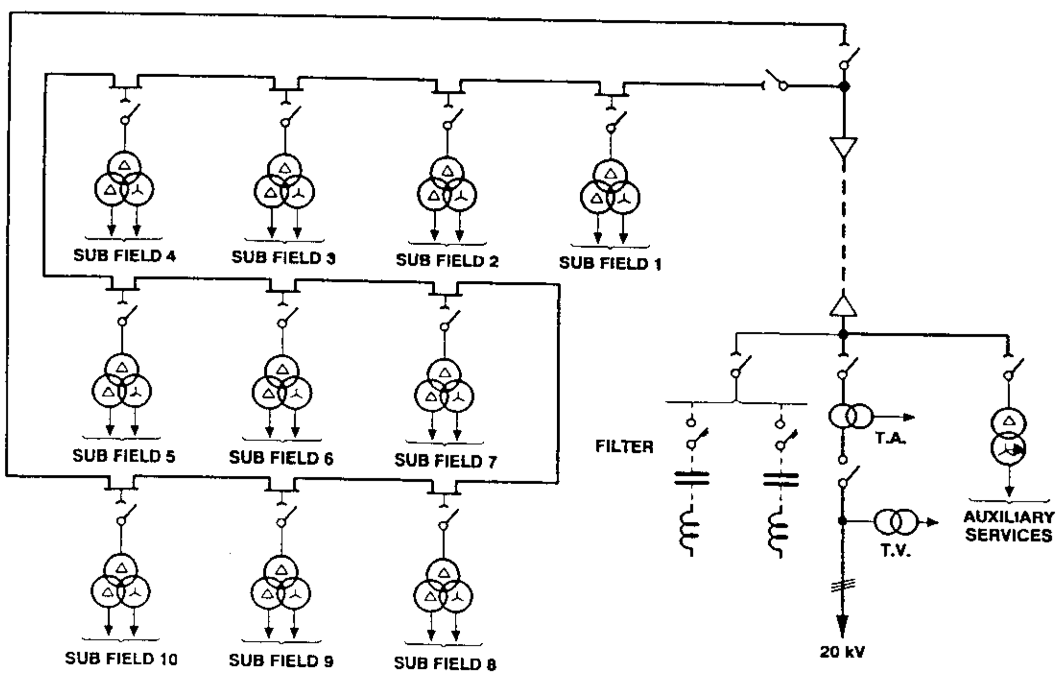

Fig. 4. 3MWp PV power plant - Topographic lay-out of 10 sub fields

7. CONCLUSIONS

The ENEL 3-MW photovoltaic power plant will be set up during the period 1991-93. Three sub-arrays are expected to come on stream by the end of '92, and the remainder thereafter. The plant will be located in the Province of Salerno (Italy). The design criteria adopted for the plant are aimed at cost optimization. It is considered that, given the experience gained in such a project, it should be possible to modify or confirm the validity of such criteria with a view to setting up other multi-MW power plants in the future.

REFERENCES

(1) Chimento G., "Determination of optimum tilt angle of panels in large scale PV arrays", (1991), Proceedings 10 th European PV Solar Energy Conference.

(2) Ross R.G., "Flat-Plate Photovoltaic array design optimization", (1980), Proceedings IEEE Photovoltaic Specialists Conference.

(3) Gonzales C., "Circuit design considerations for photovoltaic modules and systems", (1980), Proceedings IEEE Photovoltaic Specialists Conference.

(4) Arcidiacono V., "Maximum power point tracker for photovoltaic power plants", (1982), Proceedings IEEE Photovoltaic Specialists Conference.

PERFORMANCE OF DIFFERENT TYPES OF BATTERY CHARGE REGULATORS IN STAND-ALONE PV SYSTEMS

A. Iliceto (*), A. Previ (*), S. Guastella (**), A. Pappalardo (**)

(*) ENEL-DSR-CREL
Via A. Volta, 1
20093 Cologno Monzese (MI)
Italy
Tel. +39-2-88471
Fax +39-2-88475465

(**) CONPHOEBUS Scrl
Zona industriale Casella postale
95030 Piano d'Arci (CT)
Italy
Tel. +39-95-291407
Fax +39-95-291246

ABSTRACT - Performance of photovoltaic systems with electrochemical storage is affected by the adopted battery charge regulator and the problem of an optimum charge regulation in small PV plants is still an open question. To determine the optimum regulation type a monitoring activity has been carried out by ENEL and Conphoebus. Photovoltaic systems, with identical electrical characteristics but using different types of charge regulators, have been compared for a long time, at Conphoebus test facilities, in order to evaluate performance of each charge regulation strategy under identical meteorological conditions, initial battery state-of-charge and electrical load. Furthermore different types of charge regulators, presently available on the market, are adopted in PV plants run by ENEL in order to assess their efficiency and reliability: performance data of different systems have been evaluated.

1. INTRODUCTION

Battery charge regulators are included in most photovoltaic systems to protect the batteries from overcharge and excessive discharge, extend battery life and maintain battery voltage within a range acceptable for the load operation. Moreover regulators are used to transfer energy from the PV array to the battery and towards the load with the maximum efficiency. A good regulator must carry out the aforementioned tasks offering also :

- reliability;
- simplicity of manufacture;
- low cost.

The most utilized kinds of charge regulation in PV systems with electrochemical storage are:

- direct connection regulation, between PV generator and storage (see Fig. 1a) using the self-regulating capacity of properly designed PV modules when they are connected to the electrochemical storage: increasing the battery voltage increases PV array voltage and, therefore, decreases PV array current; this regulation is convenient when the PV system is placed in locations where the ambient temperature does not vary dramatically (so the PV maximum-power voltage remains fairly constant) and when the electric load doesn't require a fair constant input voltage;
- ON-OFF regulation, which consists of a complete connection or disconnection of PV generator from storage when the battery voltage gets the preset levels; the PV generator can be left in open circuit condition (ON-OFF series regulation, see Fig. 1b) or shunted to a power dissipation device (ON-OFF shunt regulation, see Fig. 1c);
- multi-step regulation, which prevents battery overcharging by a partial connection or disconnection of PV generator from storage when the battery voltage reaches the preset limits; the regulation can be realized by means of a partial connection or complete disconnection of whole strings (see Fig. 1d) or part of a string;
- chopper regulation, which maintains a fairly constant output voltage, by means of electronic devices that modulate the charge current according to the battery voltage level (see Fig. 1e);
- MPPT regulation, in which a Maximum Power Point Tracker forces the PV array to always work at its maximum power point even if the irradiance and temperature change (see Fig. 1f).

Regulators, which present simpler manufacture (like direct connection and series types), are less expensive and more reliable. On the other hand, more complex regulators, like chopper and MPPT types, present higher charging efficiency, extend battery life, but make the overall system more expensive and less reliable, because of the added circuitry.

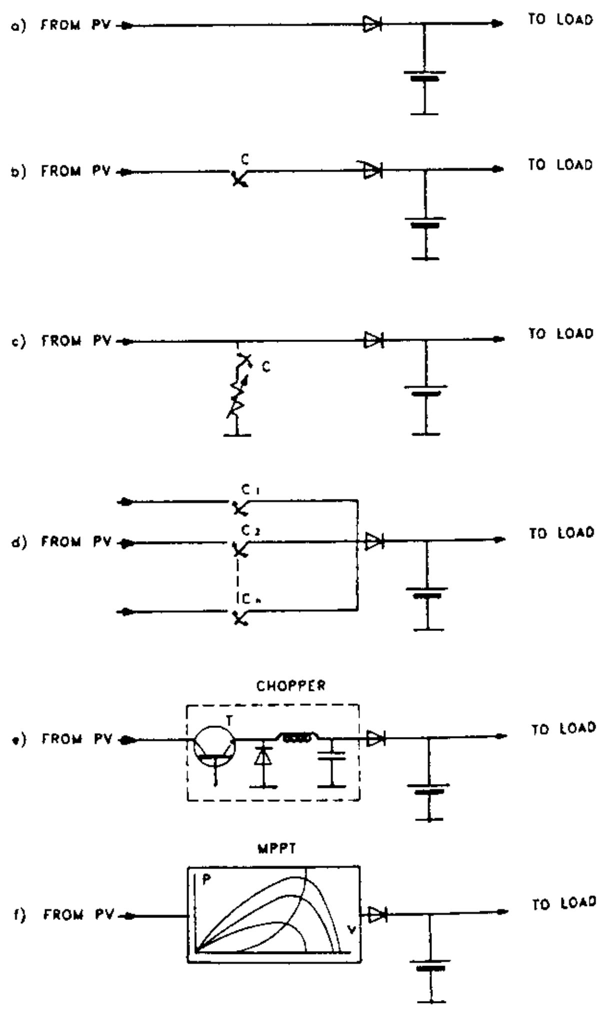

Fig. 1 Battery charge regulation for stand-alone PV systems with electrochemical storage: a) direct connection; b) ON-OFF series regulation; c) ON-OFF shunt regulation; d) multi-step regulation; e) chopper regulation; f) MPPT regulation

In order to determine the optimum regulation type the performances of stand-alone PV systems, having identical electrical characteristics but different types of charge regulation, have been evaluated under identical meteorological conditions, initial battery state-of-charge and electrical load. The work has been conducted at Conphoebus test facilities on behalf of ENEL-DSR-CREL, which has adopted different types of charge regulators for the installations in Alpine Huts /1/ and in Stromboli Island in the frame of the Scattered Dwelling Project /2/. The research has then been aimed at assessing the efficiency and reliability of various types of regulators presently available on the market.

2. COMPARISON BETWEEN 3 DIFFERENT CHARGE REGULATORS UNDER IDENTICAL TEST CONDITIONS

In order to analyze the performance of different charge regulators, during actual operations, three photovoltaic systems with identical electrical characteristics (24 Vdc rated voltage, 4 module pv generator, appropriate load and battery) have been set up in Conphoebus test facilities.

2.1 Description of the systems to be compared

The three photovoltaic systems adopt different types of charge regulators (see Tab. 1):

- ON-OFF series charge regulation is adopted in system 1; it controls the battery by means of a complete connection or disconnection of PV generator from storage when the battery voltage reaches the preset levels;
- two-step series charge regulation is adopted in system 2; it controls the battery connecting or disconnecting half PV generator from storage when the battery voltage reaches the preset levels; the second half is disconnected if the voltage reaches again the threshold;
- direct connection regulation is adopted in system 3; to obtain an optimal self-regulation PV modules must be chosen taking into account battery nominal voltage and average ambient temperature of installation site; Fig. 2 shows different self-regulation characteristics adopting PV modules with 36, 30 and 27 cells in series. A module configuration with 30 cells in series was chosen, because several test runs, conducted during some seasons, have actually indicated that this kind of module, connected with a 12 V battery, presents an optimal self-regulation capacity in the Mediterranean climate. One year operation of a PV system, using this regulation type, resulted in the PV generator presenting a conversion efficiency variable between 8.1% (during July) and 11.9% (during December and January) (see Fig. 3). The system has always charged the battery regularly and deficit occurred only in January (125 hours) and in December (59 hours); the maximum values of the battery got 31.8 V (in February), while its daily average value varied between 24.7 V and 26.2 V; in any case, during the same period, no evident electrolyte gassing was observed.

Tab. 1 - Main characteristics of tested systems

SYSTEM	1	2	3
PV GENERATOR			
Cells in series	36	36	30
Modules in series	2	2	2
Total modules	4	4	4
Total Voc [V]	40.0	40.0	35.5
Total power [Wp]	190	190	160
BATTERY			
Elements in series	12	12	12
Nominal Voltage [V]	24	24	24
Capacity C10 [Ah]	150	150	150
CHARGE REGULATION	ON-OFF series	Two-step series	Direct coupling

The compared regulation types were selected because they seem to offer more advantages than the others when used in stand-alone PV systems. In particular system 3, which adopts the regulation by means of direct coupling between PV generator and battery, for its simplicity seems the best solution for PV systems installed in remote areas, where difficulties in system maintenance could limit system operation.

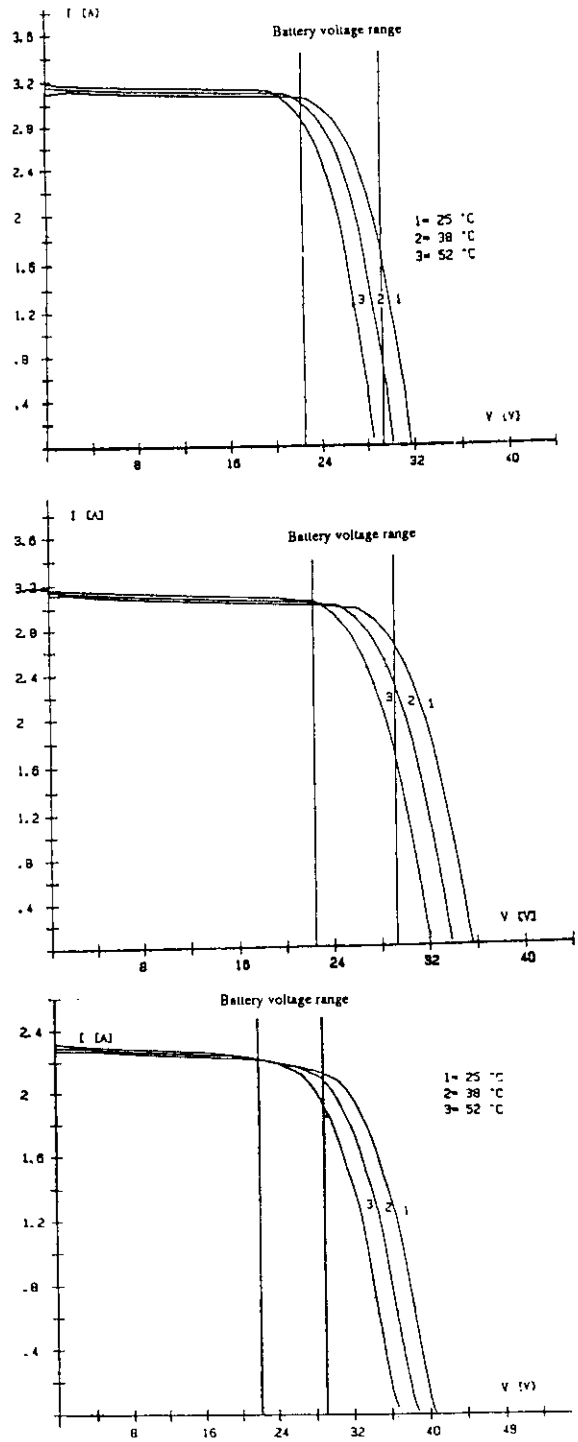

Fig. 2 Self-regulation capacity of modules with different number of cells in series: a) 27 cells; b) 30 cells; c) 36 cells

operation, a data acquisition equipment was used to monitor the main electrical and meteorological parameters. Measurements were taken every 20 seconds and their average recorded every 15 minutes. Finally the data were processed to prepare the output.

2.2 Comparison among different charge regulators during a sunny day

Fig. 4 shows the different profiles of charge current in system 2 and system 3, on a sunny day: generator-battery direct coupling allows the battery to be charged more regularly, thus avoiding high voltage fluctuations and frequent inversions of battery current, which reduces efficiency in transferring energy between PV generator, battery and load. System 3 has presented fewer battery current inversions (BCI) and has produced 36% more energy per unit of installed power than the system 2. On the same day, the maximum voltage level reached in the system 3 (31 V) is higher than that got by the system 1 and 2 (29 V), but this high value does not damage for the battery, because when the maximum value is reached the PV generator works near open circuit condition and the charge current is very low (no appreciable gas development was observed). Moreover such a voltage is affordable by the usual 24 Vdc appliances.

2.3 One month comparison among different charge regulators in no-load conditions

For one month, in two different periods, the systems were operated without load, in order to test system limits in the high charge current / low load demand condition.

Before starting the tests, the battery of each system was discharged until electrolyte density reached the value 1.18 g/cm³ (Vb = 23V). During the tests the main electrical and meteorological parameters were monitored.

Fig. 5, Fig. 6 and Tab. 2 account for the fact that the direct coupling allows higher charging efficiency than the other regulation strategies: more energy was generated and a higher state of charge was reached (see electrolyte density profile), still maintaining the battery maximum voltage within acceptable value.

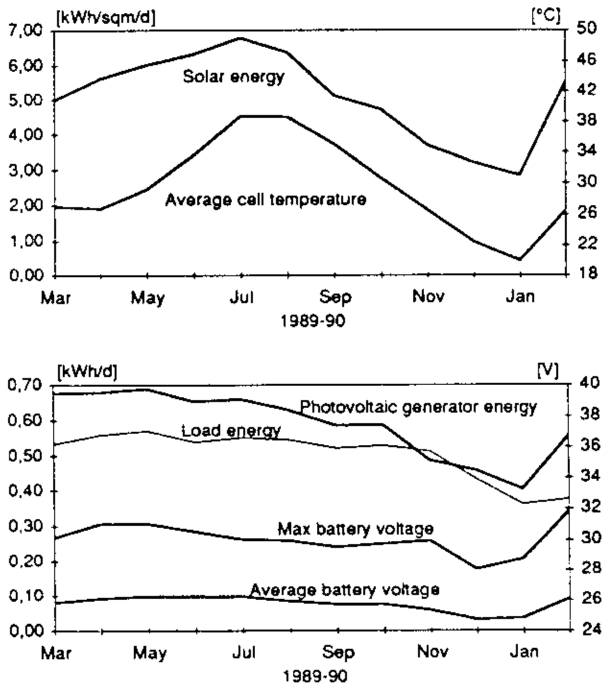

Fig. 3 One year operation of a PV system adopting direct connection regulation

normal operation

The systems under test have been compared during normal operation in different seasons.

During operation in summer period the system 3 produced, per unit of installed power, 18% more energy than the systems 1 and 2 which produced the same energy (see Fig. 7). The battery current inversion per day (BCI) were equals 55 for the first system, 21 for the second one, 6 for the third one.

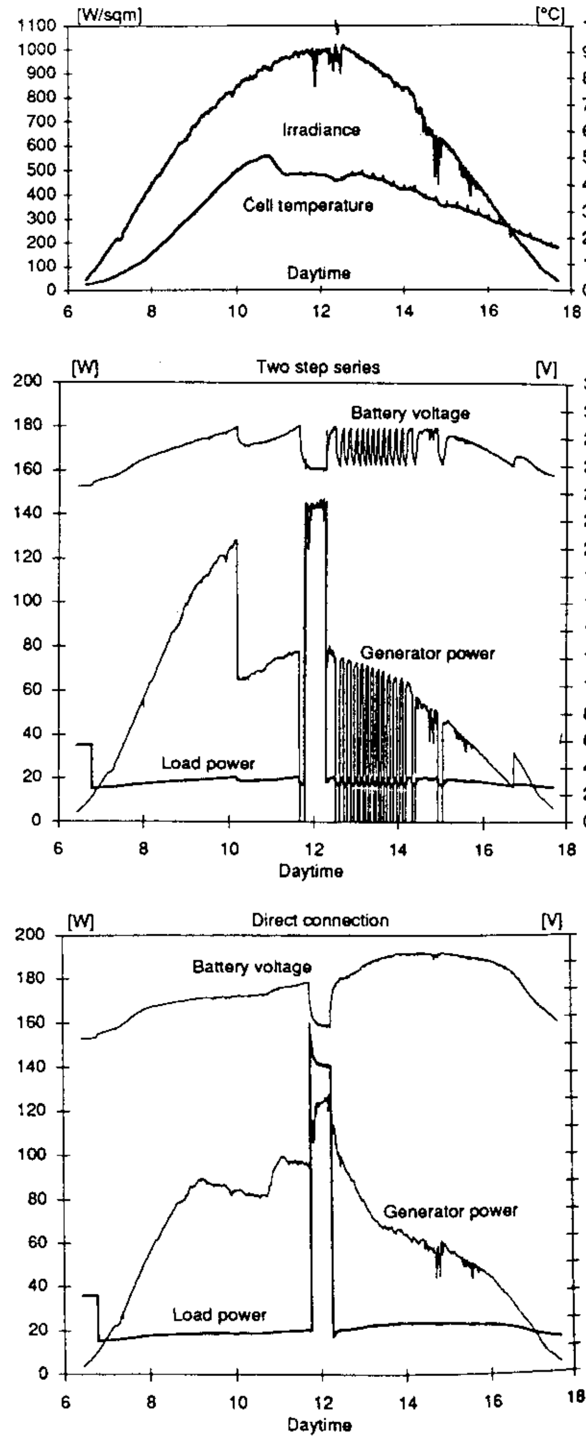

Fig. 4 - Comparison among different charge regulators during a sunny day (23/03/90).
On plane sol. radiat.. = 6940 Wh/sqm;
Average cell temp. = 29 °C;
2 step regulator: Pg = 617 Wh, Pc = 549 Wh, BCI = 40
Direct connection: Pg = 709 Wh, Pc = 574 Wh, BCI = 4

During operation in winter period the system 3 produced, per unit of installed power, 10% more energy than the systems 1 and 2 which produced almost the same energy (see Fig. 8). The battery current inversion per day (BCI) were equals 14 for the first system, 8 for the second and the third ones.

3. PERFORMANCE OF DIFFERENT CHARGE REGULATORS ADOPTED IN ENEL'S PV PLANTS

Different types of battery charge regulators have been adopted by ENEL for stand - alone PV plants, namely in 7 mountain huts and in 30 houses in the island of Stromboli, near Sicily.

The plants for the huts equipped with ON-OFF regulators have shown that the battery is not allowed to reach the initial S.O.C., thus reducing in practice the available battery capacity /1/.

At Stromboli, ten of the plants are equipped with electromechanical two-step series charge regulators, eleven plants adopt a four-step regulation by means of a programmable logical controller (PLC) and nine plants use chopper regulation. During two year operation, all the adopted regulators have presented a good reliability. The conversion efficiency of the systems which adopt PLC and chopper was quite similar and about 10% higher of the systems adopting two-step regulator (see Fig. 9). Anyway, the system efficiency is strongly affected by the user, depending upon the balance of produced and consumed energy.

4. CONCLUSIONS

According to the performance of several small stand-alone PV systems operated by ENEL, the use of simple battery charge regulators is recommended, since chopper regulators does not show drastic advantages as compared with step regulators. Furthermore the test activity carried out by Conphoebus shows that the charge regulation obtained by means of direct coupling between properly designed PV generator and battery offers reliability and efficiency. This regulation could therefore be considered the best solution for small PV systems especially if they are installed in remote areas, where difficulties in system maintenance could limit plant operation.

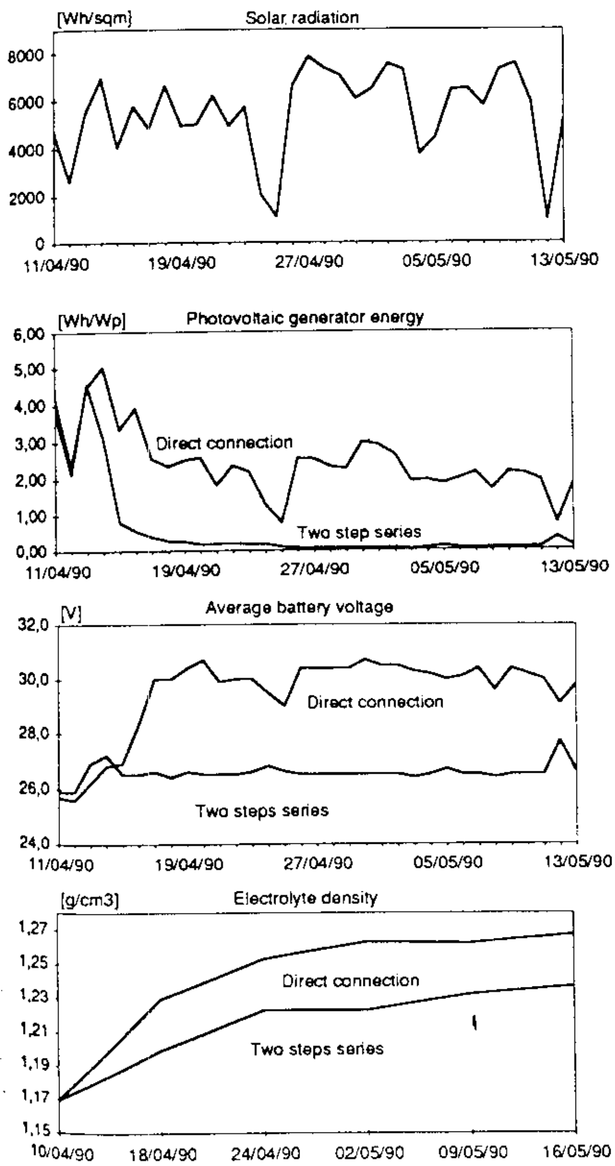

Fig. 5 One month comparison among different charge regulators in no-load conditions (April - May 1990)

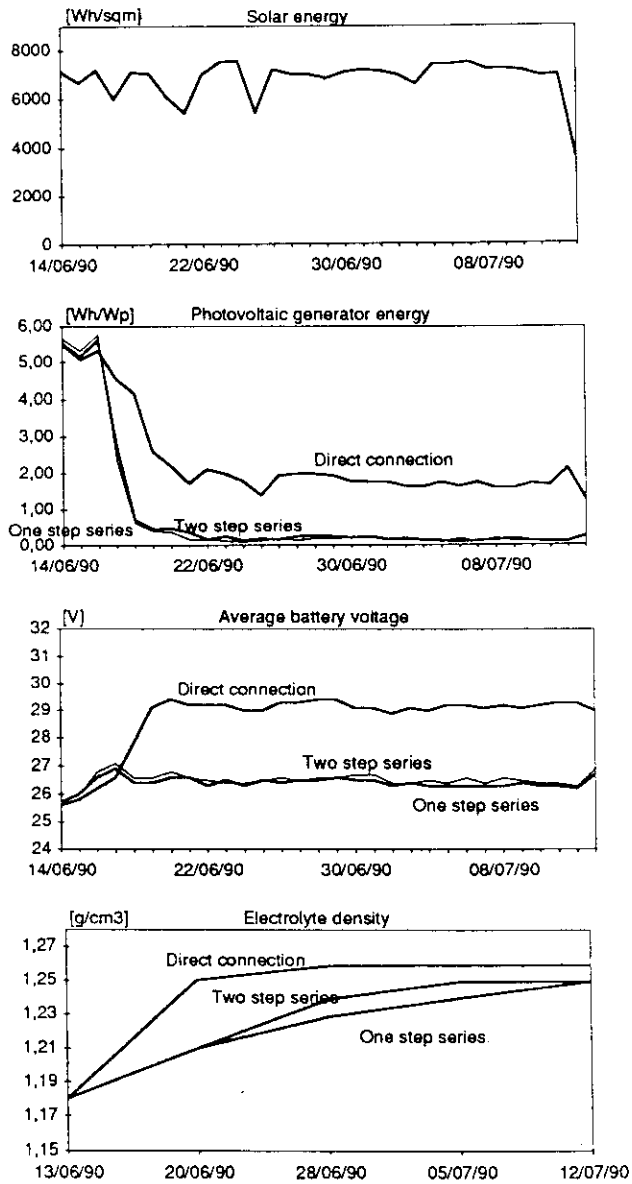

Fig. 6 One month comparison among different charge regulators in no-load conditions (June - July 1990)

REFERENCES

/1/ G. Belli, A. Iliceto, A. Previ - PV plants for Alpine huts: installation and operating experiences at seven Enel plants - 8th EC Photovoltaic Solar Energy Conference, Florence, May 1988

/2/ A. Previ, A. Taschini - Photovoltaic plants as means of supplying electricity to isolated dwellings - 5th EC Photovoltaic Solar Energy Conference, Athens, October 1983

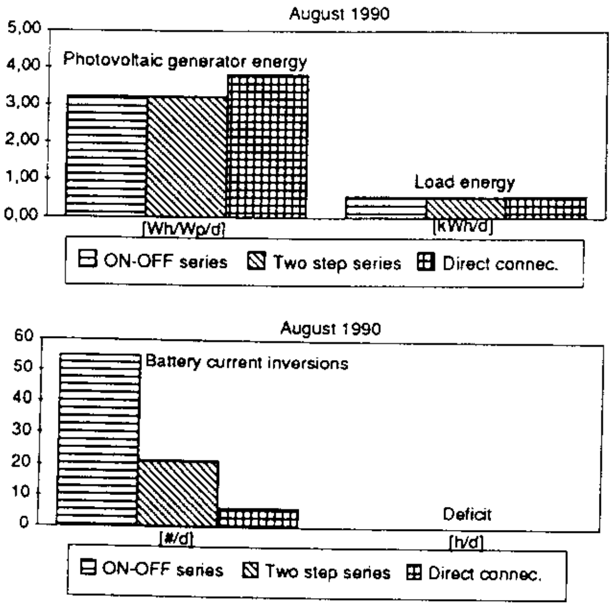

Fig. 7 Comparison among different charge regulators in actual operating conditions in a summer period

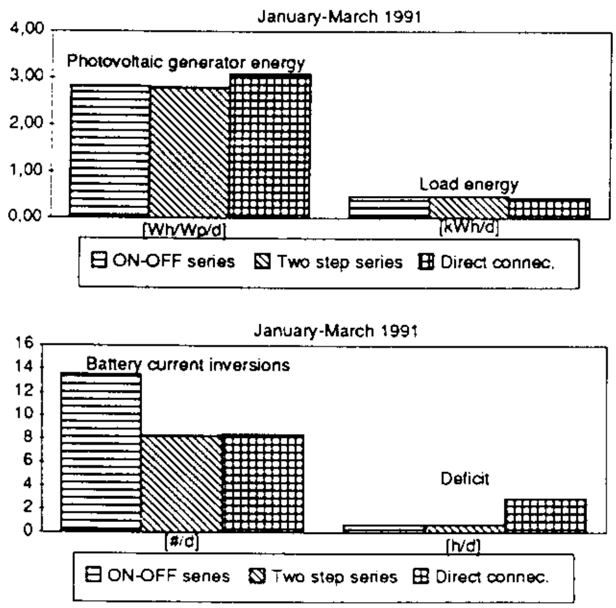

Fig. 8 Comparison among different charge regulators in actual operating conditions in a winter period

Tab. 2 Performances of tested PV systems in different periods referred to the system 2

PERIOD		April '90	June '90
On plane irradiance	[Wh/sqm/d]	5457	6800
Cell temperature during insulation time	med [°C]	20.4	39.3
	max [°C]	56.1	58.4
SYSTEM 1			
Generated energy	[Wh/Wp/d]	0.54	0.80
	[%]	-2	-3
Charge current	[Ah]	122	165
	[%]	-3	-3
Battery voltage	med [V]	26.5	26.5
	max [V]	28.9	28.9
SYSTEM 2			
Generated energy	[Wh/Wp/d]	0.55	0.82
	[%]	--	--
Charge current	[Ah]	126	170
	[%]	--	--
Battery voltage	med [V]	26.6	26.4
	max [V]	29.1	29.0
SYSTEM 3			
Generated energy	[Wh/Wp/d]	2.42	2.33
	[%]	337	192
Charge current	[Ah]	423	384
	[%]	236	132
Battery voltage	med [V]	29.5	28.7
	max [V]	32.1	30.6

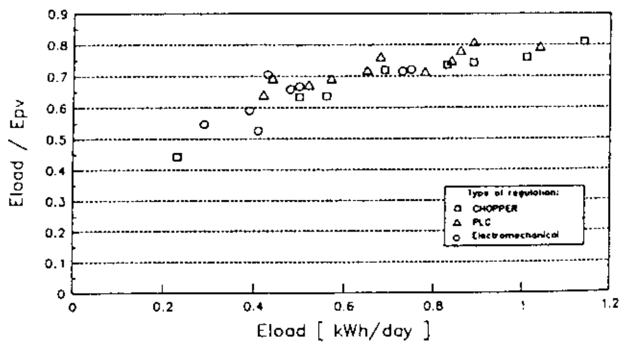

Fig. 9 Ginostra PV plants - Efficiency vs energy consumption

PROGRESS REPORT ON THE 3.3 MWp PHOTOVOLTAIC PLANT BEING SET UP BY ENEL AT SERRE (SOUTHERN ITALY)

A.Iliceto, A.Previ (*) - S.Corsi (**) - G.Belcastro, R.Vigotti (***)

(*) ENEL S.p.A.- CREL - via Volta, 1 - Cologno Monzese (MI) - Italy
(**) ENEL S.p.A.- CRA - via Volta, 1 - Cologno Monzese (MI) - Italy
(***) ENEL S.p.A.- DSR - via G.B.Martini, 3 - Roma - Italy

ABSTRACT: Plans for a 3.3 MWp PV plant at Serre were finalized by ENEL in 1991. The plant is presently under construction and will be completed by mid 1994. It consists of ten indipendent sub-arrays of 330 kWp each, equipped with semi-crystalline modules, connected in parallel to the MV grid by means of line-communitated MPPT inverters. The main features of the plant, procurement criteria, current situation and cost analysis are presented in the paper.

1. INTRODUCTION

ENEL's decision to build the photovoltaic power station at Serre was taken in 1990 mainly with the aim of checking the technical-economic feasibility of photovoltaic power plants designed for use by electric utilities.

The project also had the aim of providing a boost to the national photovoltaic industry, as well as enabling technical know-how to be acquired in an energy sector in a phase of expansion.

The general project for the plant was completed during 1991, when also the technical specifications required for the acquisition of the components were defined, and orders for the equipment and assemblies were placed.

2. GENERAL DESCRIPTION OF THE PLANT

The main feature of the power stations's architecture (see Fig.1) is the subdivision of the plant in ten electrically independent subfields of 330 kWp each, linked to a MV ring terminating at a central cabinet [1].

Each photovoltaic subfield is fitted with an autonomous MPPT inverter with step-up transformer, housed in a small cabinet barycentric to the subfield concerned.

A central building houses the equipment for interfacing with the electrical network, the supervision and data acquisition system and the auxiliary services.

2.1 Modules

The photovoltaic modules are made of semi-crystalline silicon, with 36 or 72 4" or 5" cells per module.

The total number of modules is about 60,000, corresponding to over 2,600,000 cells.

2.2 Photovoltaic Subfields

The ten 330 kWp subfields are mounted on fixed metal supporting structures, with an angle of inclination of 20 degrees [2] (see Fig. 2).

The structures are in the form of lattice frameworks, they require, for the overall plant, over 700 tons of steel (210 kg/kWp), and are anchored in foundations requiring about 2600 cubic metres (0.79 m^3 /kW) of reinforced concrete (35 kg Fe/m^3) per subfield.

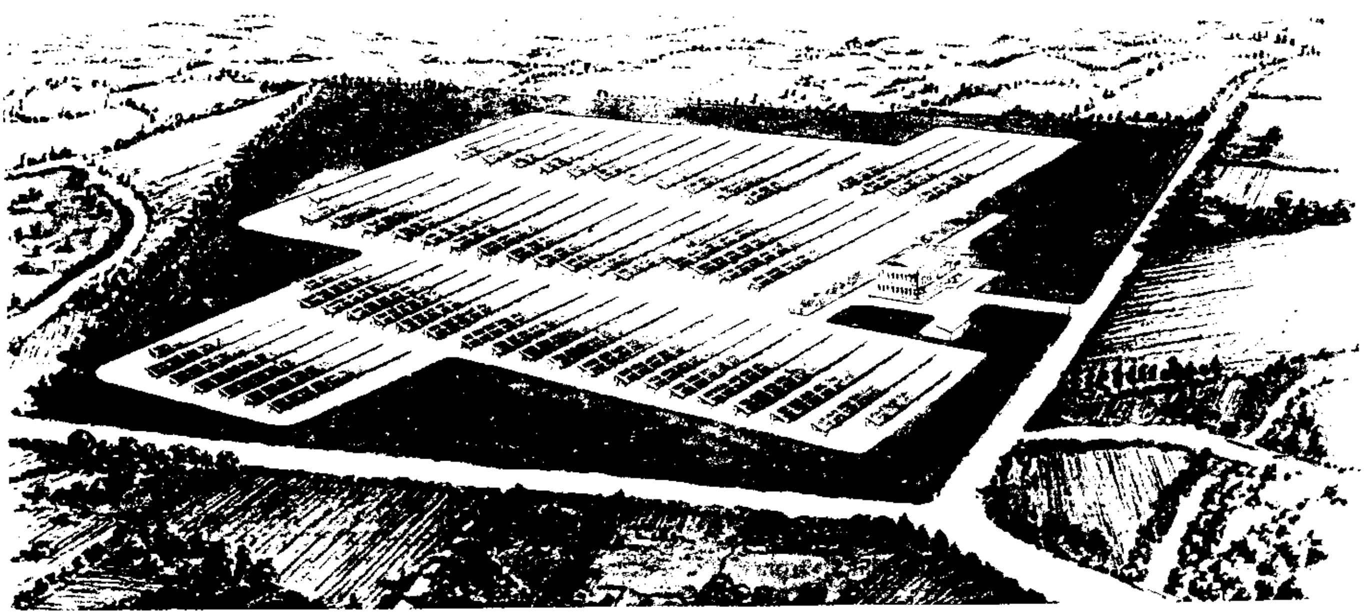

Figure 1: Artistic View of ENEL's 3.3 MWp PV Plant

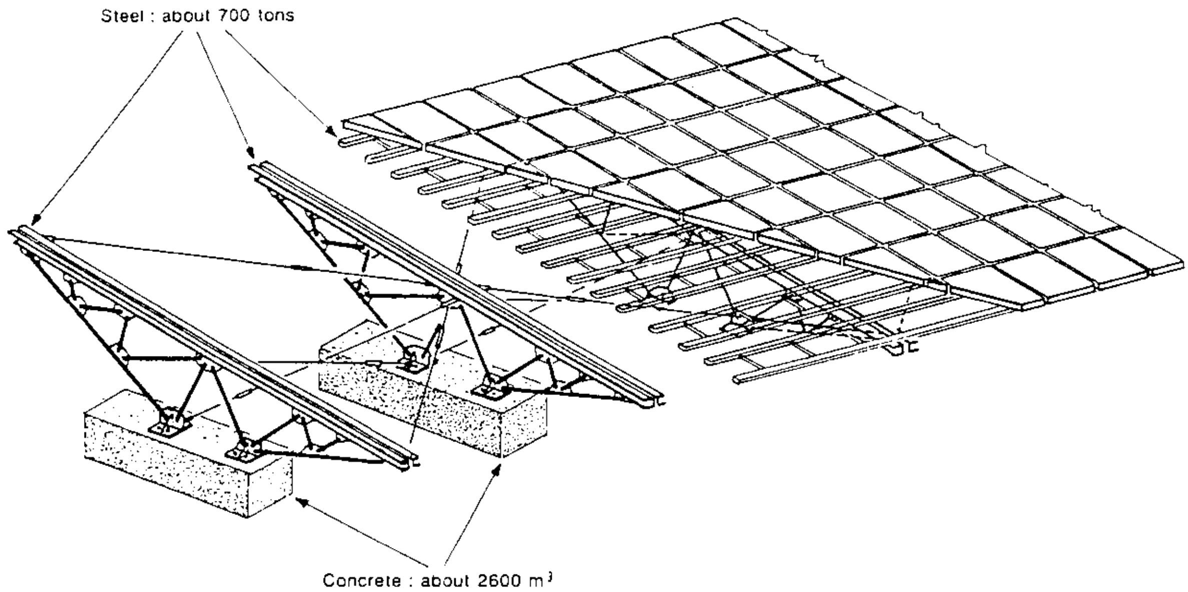

Figure 2: Sketch of the supporting structures

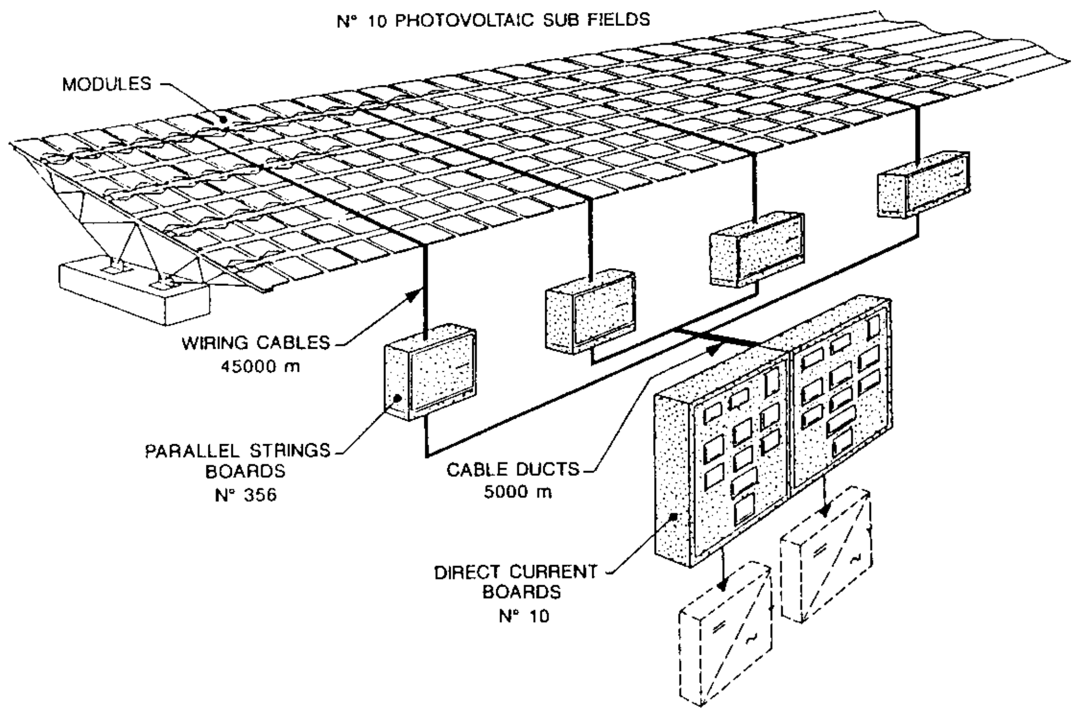

Figure 3: DC electrical system

2.3 DC Electrical System

The DC electrical system (see Fig. 3) is made up of connections between the modules, in series of 10 or 20, with a string voltage of about 330 Vn (440 Voc). Groups of 80 or 160 modules terminate at peripheral small cabinets for parallel connections (about 35 per subfield).

From these cabinets, a number of cables laid in cable-ducts reach an electric board housed in a small cabin, positioned barycentrically in each subfield. This board supplies the adjacent subfield inverter.

The DC electrical system is insulated from ground.

The total length of the DC cables is about 5000 m per subfield (500 of which laid in buried cable ducts).

2.4 Inverters

The ten inverters are of the line communtated type, with a nominal power of 550 kVA.

Each inverter comprises two galvanically insulated power units (see Fig. 4) fitted with tyristors connected to the LV side of the step-up transformer.

The inverters are fitted with a control system that enables them to function in MPPT or at impressed voltage, and allows the sweeping of the I-V characteristics.

The efficiency is 95% at Pn and above 90% at 25% Pn.

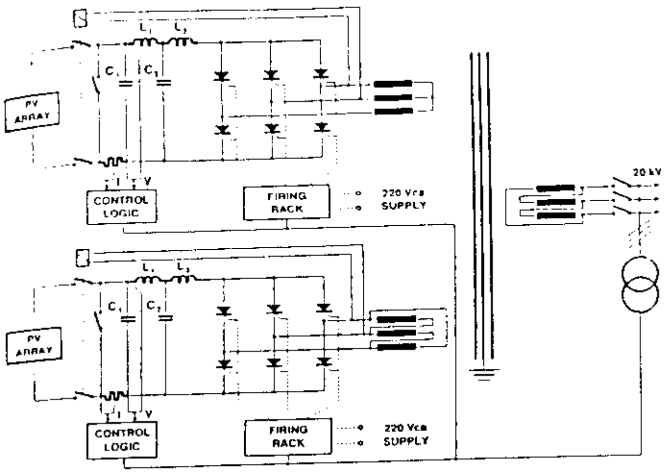

Figure 4: Each inverter consists of two galvanically insulated tyristor bridges, connected to a transformer

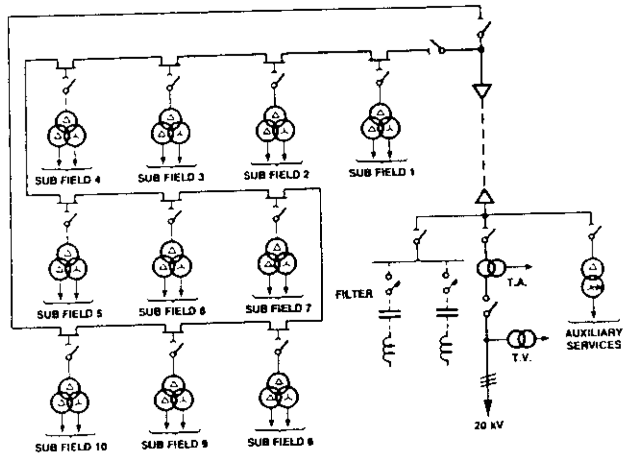

Figure 5: AC electrical system (n° 10 step-up transformers connected to a 20 kV cable; central filtering and power factor compensation; grid interface)

2.5 AC Electrical System

Each subfield inverter is connected to a double secondary transformer D-Y, with a primary D, 550 kVA rated. This is connected, via a MV switch, to a buried 20 kV cable ring of about 2500 m, which terminates at the MV cabin for interfacing with the electrical distribution network.

This cabin also contains the system for filtering the harmonics and compensating the reactive power, and the auxiliary AC and DC services (see Fig. 5).

2.6 Centralized Supervision and Data Acquisition System

For experimental and demonstration purposes, the power station is equipped with a centralized supervising, monitoring and data acquisition system, which makes it possible to observe, online, the functioning of the plant, execution of electrical manoeuvres, and the acquisition and processing of both electrical and meteorological data (see Fig. 6).

2.7 Civil Construction Work

Preparation of the site involves the removal of 10,000 m^3 of earth in order to create three flat areas, which cover a total of 70,000 m^2. The cover coefficient is about 0.45. The perimeter fencing extends for about 1,500 m. The asphalted roads inside the area, which are 4 m wide, extend for about 1,200 m. Suitable drainage work will be provided. The ground network will require 5,000 kg of copper.

The buildings provided comprise a prefabricated cabin for each subfield, which houses the DC electrical subfield and the inverter, and a central building that houses the interfacing with the network and the auxiliary services and, for demonstration purposes, the supervision and a meeting room.

The buildings occupy a total of about 1,000 m^3 for the electrical systems, 400 for working areas, and about 900 for research and demonstration activities.

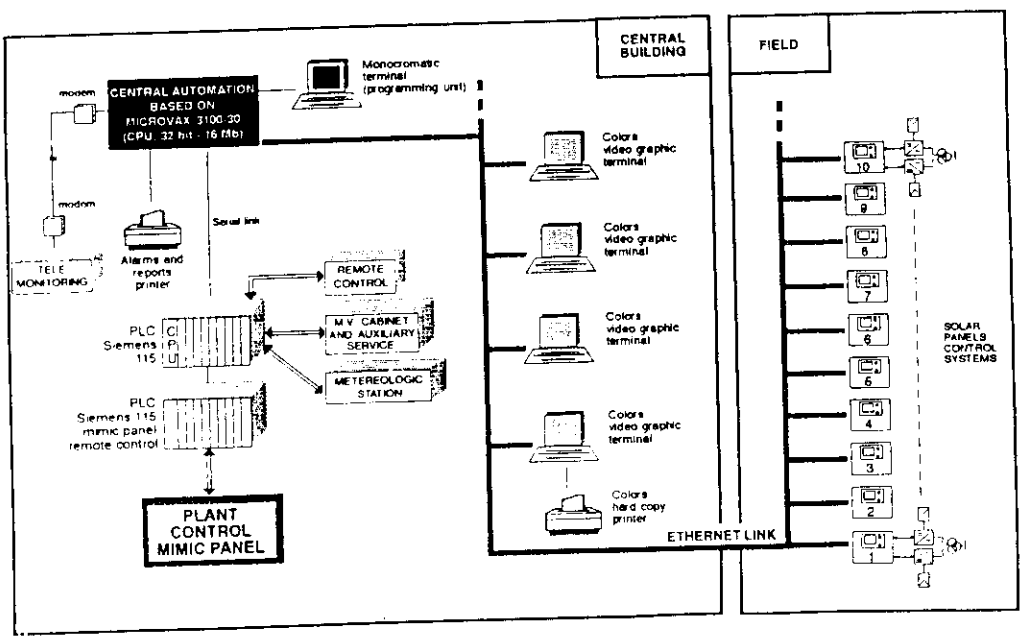

Figure 6: Centralized supervision and data acquisition system

3. PROCUREMENT CRITERIA

Supplies for the 3.3 MW power station are subdivided in three items: modules, inverters and BOS.

It has been decided that the modules, following an international technical-economic survey, be supplied by five Italian and foreign manufacturers of multi-crystalline silicon modules.

A sample shipment of these modules, which are manufactured according to ENEL specifications, has been made for type testing (CEC-JRC 503 certification and additional insulation tests).

The acceptance tests are effected at the factories of the suppliers: they are carried out on samples, selected according to standard sampling tecniques, and are based on a predefined classification of defects that involves the acceptance, reworking or rejection of the lot being examined.

The final testing is performed during the preassembly of the modules in panels, with 100% in situ checks of the electrical characteristics, prior to mounting on the supporting structures.

The inverters are manufactured in accordance with a detailed ENEL design and are supplied following a tender. A prototype is subjected to type testing, and the ten units supplied are checked at acceptance trials.

The balance of system, which comprises the executive project, all the components supplies, all the site work and the start-up phase, has been awarded following a tender based on a general ENEL plan.

Type and acceptance testing are provided for all qualifying components, along with periodic checks of the site works, up to the final testing and plant start-up phases.

4. CURRENT SITUATION AND SCHEDULE

During September 1992 type testing was in progress on a number of photovoltaic modules, while other lots of modules were undergoing acceptance trials.

It is expected that half the total number of modules will be supplied by mid 1993.

As regards the power conditioning, type tests are in progress on the prototype inverter, and the ten units ordered for the plant will be available by mid 1993.

As regards the BOS, to date, the plant executive project has been completed and approved, and the on-site work was begun in September 1992; the plant will come on stram gradually: 1300 kWp will be connected to the grid by August 1993, 1000 kWp by December and the remaining 1000 kWp by mid 1994.

5. COST ANALYSIS

The total cost of the plant is estimated at a value of about 7000 ECU/kWp, of which about 5% covers equipment and systems concerning research or demonstration.

The breakdown of the total capital cost into the various components is shown in Fig.7: the modules contribute for about 60% of the total.

AKNOWLEDGMENTS

The authors wish to thank Carlo Gavazzi Systems, Cesi and Fit-Ferrotubi for their cooperation

REFERENCES

[1] C. Corvi, R. Vigotti, A. Iliceto, A. Previ, "ENEL's 3-MW PV Power Station Preliminary Design", Proceedings 10th European PV Solar Energy Conference - Lisbon - April '91

[2] A. Iliceto, A. Previ, G. Chimento, S. Guastella, "Detemination of Optimum Tilt Angle of Panels in Large Scale Photovoltaic Arrays", 10th European PV Solar Energy Conference - Lisbon - April '91.

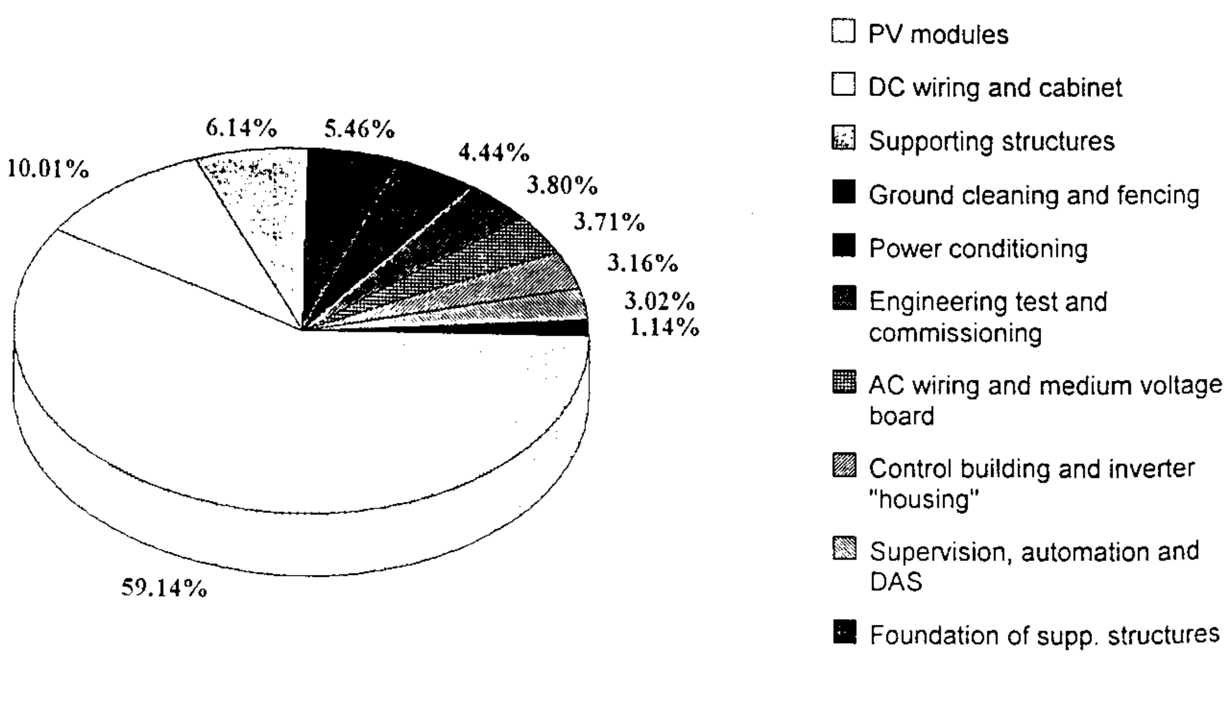

Figure 7: Breakdown of the total capital cost of ENEL's 3.3 MWp PV plant

ENEL'S TEN YEARS' EXPERIENCE IN THE USE OF PHOTOVOLTAIC GENERATION UNITS TO SUPPLY ISOLATED DWELLINGS WITH ELECTRICITY

G.Belli, A.Iliceto, A.Previ
ENEL S.p.A. - DSR - CREL
Via Volta, 1 - Cologno Monzese (MI) - Italy

ABSTRACT: In 1982 ENEL launched a technological development program for the nationwide application of photovoltaic systems, with the aim of supplying small loads to consumers and tradesmen in isolated areas not yet covered by the national electricity service.
This Report describes the main project data of the systems built by ENEL (about 250 installations) and the performance figures, where available.

1. INTRODUCTION

In 1982 ENEL launched a technological development program for the nationwide application of photovoltaic systems, with the aim of supplying small loads to consumers and tradesmen in isolated areas not yet covered by the national electricity service.

The program was structured to enable investigation of feasibility, cost, production, reliability and the level of satisfaction of users' needs. These parameters applied both to very small photovoltaic plants (able to supply not more than 1000 kWh/year), and larger plants able to produce up to 6000 kWh/year. This subdivision was made because of the necessity to provide two types of plant:
1) Plants for users requiring only modest loads, making it possible to supply electricity at 24 or 48 V dc.
2)Plants for more demanding users, requiring mono- or tri-phase AC supplies at 220-380 Vac

From 1982 to 1992, both types of system were developed to meet a number of practical applications, some of which are now in the process of being installed.

2. INSTALLATIONS

In the period 1984-1992, the following installations were completed:
- Seven plants for supplying Alpine refuges [1]
- Eight plants for supplying WWF field bases [2]
- One for the Ministry of Agriculture.
- Thirty plants for supplying homes situated in the Ginostra area of the Island of Stromboli (Sicily) [3]
- Sixteen plants for supplying homes situated in the Bazzina area of the Island of Alicudi (Sicily).

In the period 1992-1993, the following plants will be completed:
- One hundred and forty plants for supplying small tradesmen in the Southern Italian regions of Abruzzo, Molise, Puglia, Campania, Basilicata, Calabria and Sardinia (Valoren Project).
- Seven plants for supplying business users in the Ginostra area on Stromboli, Sicily.
- Eighteen plants for supplying Alpine huts.

The above plants have a peak power between 0.3 kW and 6 kW, with nominal operating voltages of 24 dc or 220 ac.

3. DESIGN CRITERIA

The plant are designed on the basis of a constant guarantee to users of a high degree of reliability in power supplies. From the quantity point of view, this is expressed as a total maximum number of hours per year for which power supplies cannot be guaranteed.

ENEL plants are normally designed to allow between zero and 100 hours per year in which supplies are not available; the exact figure in this range is dictated by users' individual requirements [4].

Non-availability depends also from random interruptions in supply due to breakdowns occurring in the plant, and failures caused by users.

To keep the levels of non-availability within the project's designed range requires extremely high plant reliability. To guarantee this, it is necessary that:
- The basic electrical design of the plant is simple and correct.
- The protections with which the plant is fitted are calibrated in accordance with the plant's general criteria.
- Both the reliability and life of the components are the highest possible.

As well as the technical criteria involved, the design of the plant is also influenced by the total implementation cost. The final design criteria thus derive from an acceptable compromise between cost and reliability.

To gain experience the ENEL demonstration program in this sector therefore varies from case to case, with the result that plant designs differ as regards the installed power, the technical solutions adopted in the basic layout, and the ways in which battery charge is controlled.

The following sections cover the main components of the stand-alone plants, and briefly describes ENEL's experiences.

4. SUBSYSTEMS: ACQUIRED EXPERIENCE

4.1 Photovoltaic Modules

Ten years' experience in the use of crystal modules (single and multi) has produced very positive results, in the sense that these components can without doubt be regarded as the most reliable of all those used in the plant. They need practically no maintenance. The photovoltaic fields used have a power of between 350 Wp and 6000 Wp depending on user requirements.

4.2 Batteries

The stationary Pb accumulators are of the type normally used in ENEL plants. The cells used have a capacity of between 300 Ah and 1500 Ah, depending on the power of the plant. The reliability of this component has been satisfactory in all the applications described in this Report.

Controlling the state of the accumulator is still a problem as regards both estimation of the state of charge and estimation of the life remaining after installation.

The above information can be obtained (approximately) by monitoring systems which, although certainly available on the market, are too sophisticated to be applied to the small systems described here.

One practical problem, but relevant also from the economic point of view, concerns the "housing" of the accumulators in the open air. The containers designed by ENEL are certainly adequate in resolving the technical problems connected with the installation of the accumulators (safety, maintenance, etc.). The cost is still very high and can only be reduced by standardization. Maintenance of the plants has not been particularly demanding, although it has always been necessary to assign ENEL technicians for the periodic site checks.

4.3 Charging Regulators of the Batteries

In the plants developed by ENEL, a number of devices have been tested for battery charging (see Fig.1), including directly connecting the photovoltaic field with the battery. All the methods used proved successful, but obviously the self-regulating system was preferred, which offers reliability at low cost [5].

What choice to make from among the various types of regulators, apart from the cost, depends on the particular conditions in which the accumulator has to work (continuous or discontinuous charge, the temperature of the environment, accumulator type, whether the capacity is high or low relative to the power of the photovoltaic field).

A good compromise between the various types of regulators is shown in Fig. 1 bis, for the following reasons:

- high reliability
- high charging capacity
- low self-consumption
- low cost.

4.4 Power conversion

As described below, ENEL has carried out experiments in supplying power to users by means of both Direct Current and Alternating Current.

In some cases it has been shown convenient to install small converters dedicated only to feeding a part of the equipment used, leaving the remaining in Direct Current.

In the more powerful plants ENEL has made a total conversion of the power, by means of autonomous converters designed ad hoc for photovoltaic systems.

The converters have a high performance level also at low charge, an extremely low self-consumption (a load sensor enables the machine to be kept on standby when the load applied is practically null), and a high level of overloading.

This equipment has been installed recently, and no data are available yet regarding reliability over time.

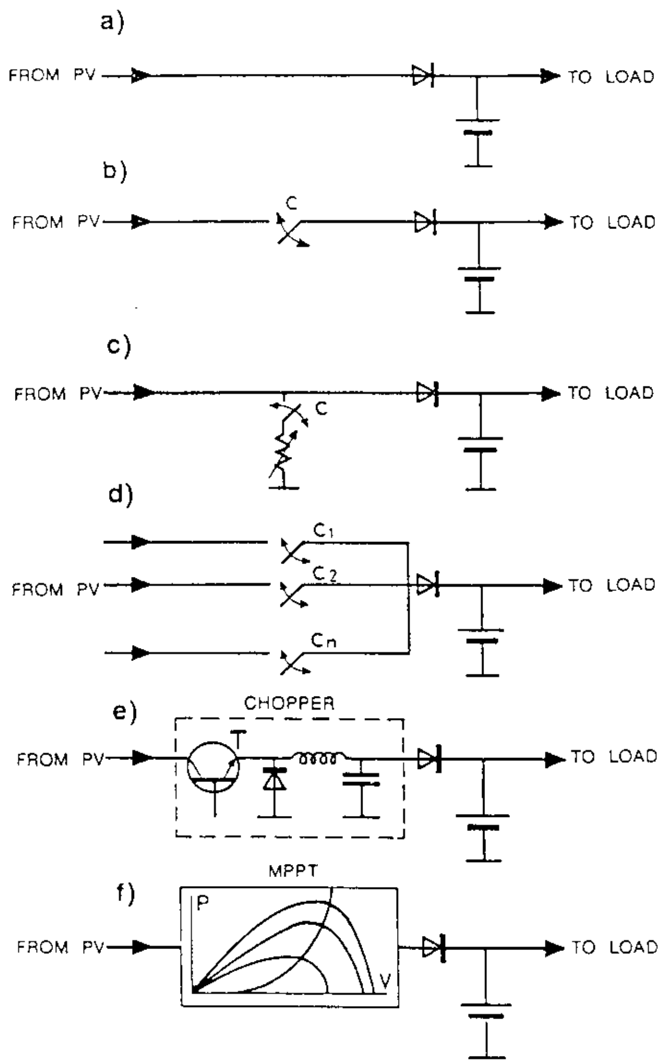

Figure 1: Battery charge regulation for stand-alone PV systems with electrochemical storage: a) direct connection; b) ON-OFF series regulation; c) ON-OFF shunt regulation; d) multi-step regulation; e) chopper regulation; f) MPPT regulation

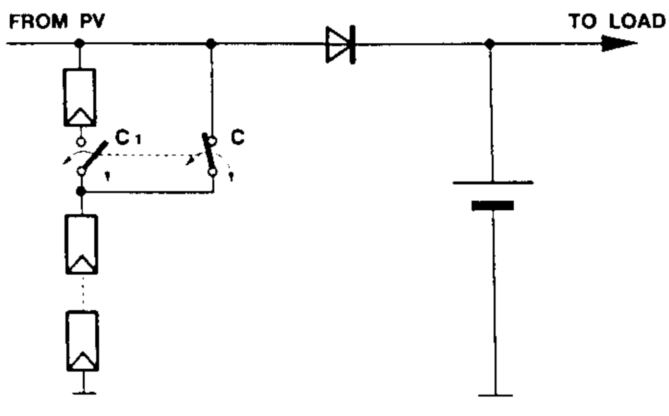

Figure 1 bis: ON-OFF shunt regulation of one PV module

The scheduled maintenance of this equipment must always be carried out by specialist technicians, either from ENEL or the manufacturer.

4.5 Monitoring

All the systems installed by ENEL are fitted with power meters (for Alternating and Direct Current), for the calculation of the power consumed by users.

ENEL has also designed and developed a special data acquisition system, which provides more detailed information on the behaviour of the plant and the reliability of the supply. This system, which is known as GMF, provides a complete energy balance report on the plant, i.e.: [6]

- The solar energy acting on the photovoltaic field
- The electrical power produced by the photovoltaic field
- The power consumed by the user
- The number and duration of the periods when the user is not supplied

The design of the GMF system required considerable care, particularly as regards reliability and the reduction of self-consumption. These measuring systems, installed for long periods in certain ENEL installations, have made it possible to characterise their behaviour completely, as described below.

In some cases, commercial data loggers have been used, integrated in the GMF systems in order to make the energy balance calculations through the continuous recording of the voltages and currents in the various sections of the plant.

5. SOME OPERATING RESULTS

The most interesting aspect, clearly confirmed by the operating results of ENEL plants, is that the stand-alone plants must almost always be designed to supply more than the actual needs of the load, particularly when the latter is for consumers. The intake of power by this type of user, as is well-known, is rarely the same on any given day, and is linked to the particular lifestyle of the people involved, to periods of absence and to the number of occupants of the premises being supplied, and so on.

The random nature of the load inevitably means that the photovoltaic plant is often larger than strictly necessary, as it must be designed to supply power to the user "in the worst case" both as regards the consumption by users and the meteorological conditions.

The above situation is well-documented by the records of the energy balances of the thirty plants installed in the Ginostra area of Stromboli. All the plants are identical (they have an installed power of 350 Wp), supply power to the user at 24 V dc, and benefit from the same levels of insolation, as they are all located in a relatively small area (about 2 sq km).

The bar chart (see Fig. 2) shows users' consumption (average daily value of the power consumed and produced over two years). It is evident that only a few users fuily exploit the potential of the plant, while the majority consumes only a small part of the electrical power available.

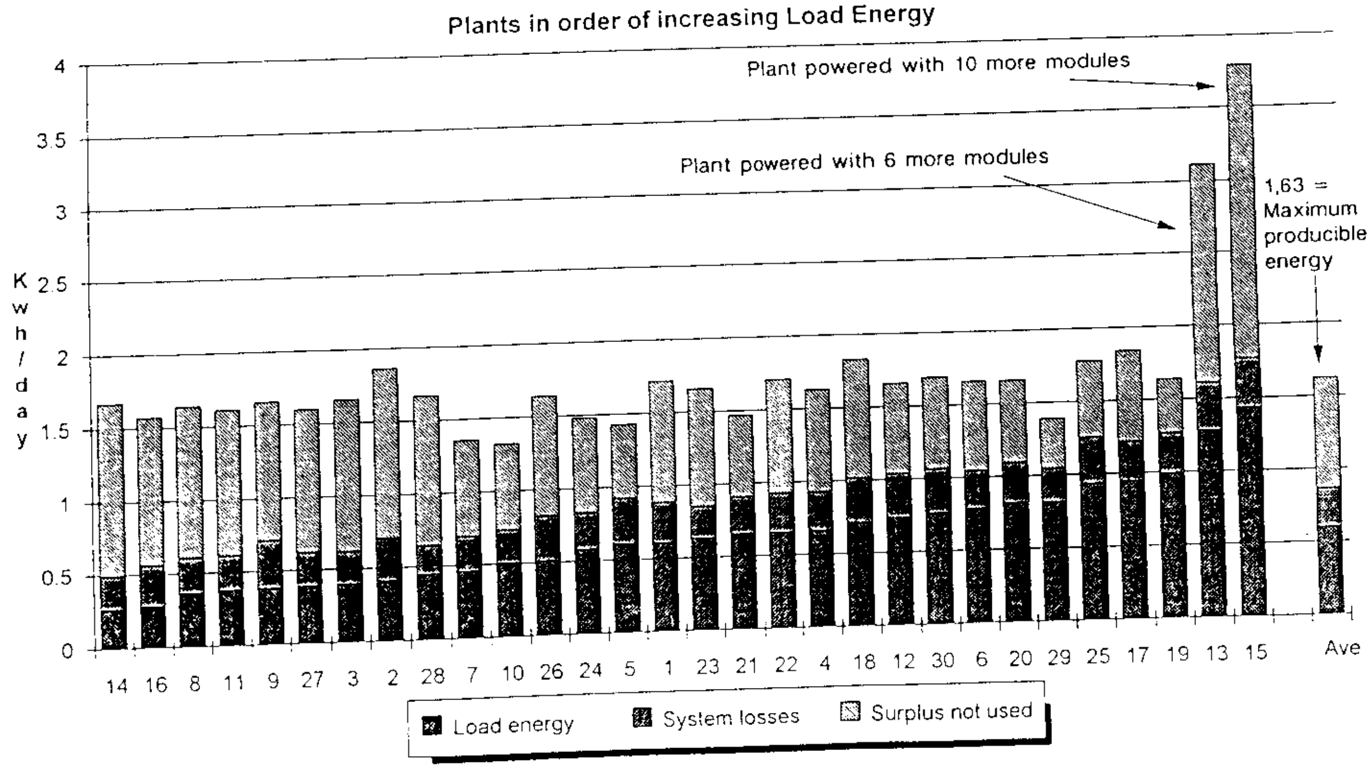

Figure 2: Energy balance in the first 2 years operation period of the 30 Ginostra PV plants

6. CONCLUSIONS

The production of decentralized electrical power at the rural premises of consumers or tradesmen is feasible even with stand-alone photovoltaic plants.

ENEL's ten years' experience in the field confirms this.

Choice of the way the power is supplied (traditional means or photovoltaic) depends on environmental and/or economic considerations. It is clear that the photovoltaic plant replaces, in this application, the traditional means of supplying electrical energy current (overhead lines or underground cables), or the Diesel generator. The "avoided" cost of the photovoltaic installation may therefore be that of the line or cable or the least quantifiable facet of reduced environmental impact, visually or acoustically.

The current cost of the plants described here is about 20 - 30 ML/kWp, and this will probably be slightly reduced by ENEL in the immediate future as the components used are further standardized.

ENEL will subject the operational costs of these plants to further analysis, particularly as regards the plants equipped with the static converter developed as part of the VALOREN project.

In the near future, ENEL will therefore also be able to count on photovoltaic systems to resolve particular problems in supplying power to users facing high connection costs, and to users located in areas that are subject to environmental controls, where the use of overhead cables is to be avoided

REFERENCES

[1] G.Belli, A.Iliceto and A.Previ, PV plants for alpine huts, Installation and operating experience at seven ENEL plants. Proceedings 8th EC Photovoltaic Solar Energy Conference (1988)

[2] G.Belli and A.Iliceto, The photovoltaic plants of Orbetello and Zannone. Proceedings 7th EC Photovoltaic Solar Energy Conference (1986)

[3] A.Iliceto and A.Previ, Solar Energy Electrification of isolated dwellings located at Ginostra. Proceedings 4th Contractors Meeting DGXVII (1989)

[4] A.Previ and A.Taschini, Photovoltaic plants as a means of supplying electricity to isolated dwellings. Proceedings 5th EC Photovoltaic Solar Energy Conference (1983)

[5] A.Iliceto, A.Previ, S.Guastella and A.Pappalardo, Performance of Different types of Battery Charge Regulators in stand-alone PV systems. Proceedings 10th EC Photovoltaic Solar Energy Conference (1991)

[6] C.Brambilla and A.Iliceto, A low-cost measurement and data acquisition system for small PV power plats. Proceedings 8th EC Photovoltaic Solar Energy Conference (1988)