1. INTRODUCTION

“PV technology, like most new technologies, has been caught in the classic «chicken-or-egg» quandary where product cost-cutting is inhibited by a lack of volume market, while market size is in turn inhibited by product cost”.

This is the syndrome to break as an essential first step toward accelerating the commercialization of PVs.

Photovoltaic literature agrees that numerous cost-effective photovoltaic measures could be undertaken, but they are not because market barriers discourage such investments. Similar arguments are used for solar thermal and energy conservation measures.

A review of these barriers indicates that, in general, they do not discourage investment and there are not market failures.

A conventional investment model suggests that business investments in photovoltaics are made with the same decision rules as any other investments.

Consumers who invest in photovoltaics require higher rates of return when the investments have a lack of liquidity and they are unable to diversify away the risk. The high discount rates required by consumers for energy-efficiency instruments reflect real costs in a competitive market, not artificial market barriers.

Photovoltaics is not an exception and in fact any photovoltaic plant composed of polycrystalline cells has an energy pay-back time, i.e. the time required to generate the same quantity of energy as was needed to build it - about six-seven years; during this period it is a "negative" electricity generator and only afterwards does it become a "positive" electricity generator.

This means that a polycrystalline photovoltaic plant during its life is not an electricity generator but rather a storage system.

New advanced technologies, still at the experimental phase, such as thin films should have energy pay-back times in the order of a few months. Indeed, it seems that for materials such as amorphous silicon it is equal to 6 months, for CIS is equal to 3-4 months and for cadmium telluride is 1.6 months.

Because of the intrinsic characteristics of PV , besides activities related to the energy sector where there is competition from other traditional energy sources, special interest comes from the interactions with other human sectors of activity and from new opportunities never implemented before with other energy sources, for instance where improvements to the quality of life in a non competitive situation are the aims.

This is demonstrated by the inconsistency of contribution which the photovoltaics can give to the world energy needs.

In the first table the world gross internal energy consumption is given in absolute values and in percentage values for the years 1973 and 1992.

In the second table the world energy availability is given again in absolute values and percentage values for years 1973 and 1992.

In the third and fourth tables some information as in the first and second tables above are given for the EU countries.

Gross Internal Energy Consumption in the World:
Absolute Values (Mtep) and Percentage Values in 1973 and 1992

WORLD	1973	(%)	1992	(%)
Solids	1568	(28)	2266	(28)
Oil Products	2825	(49)	3205	(39)
Natural Gas	978	(17)	1731	(21)
Electric Energy *(1)*	287	(5)	507	(6)
Nuclear Energy	45	(1)	468	(6)
Total	**5703**	**(100)**	**8177**	**(100)**

(1) It includes: hydroelectric, geothermoelectric, other renewable energies and import balance

World Energy Availability:
Absolute Values (TWh) and Percentage Values in 1973 and 1992

WORLD	1973	(%)	1992	(%)
Solids	2420	(39)	4727	(39)
Oil Products	1529	(25)	1362	(11)
Natural Gas	755	(12)	1650	(14)
Electric Energy *(1)*	1310	(21)	2307	(19)
Nuclear Energy	203	(3)	2094	(17)
Total	**6217**	**(100)**	**12140**	**(100)**

(1) It includes: hydroelectric, geothermoelectric, other renewable energies

EU Gross Internal Energy Consumption:
Absolute Values (Mtep) and Percentage Values in 1973 and 1992

WORLD	1973	(%)	1992	(%)
Solids	293	(26)	267	(21)
Oil Products	674	(59)	574	(45)
Natural Gas	118	(11)	229	(18)
Electric Energy *(1)*	36	(3)	44	(4)
Nuclear Energy	15	(1)	151	(12)
Total	**1136**	**(100)**	**1266**	**(100)**

(1) It includes: hydroelectric, geothermoelectric, other renewable energies and import balance

EU Energy Availability:
Absolute Values (TWh) and Percentage Values in 1973 and 1992

WORLD	1973	(%)	1992	(%)
Solids	520	(43)	760	(39)
Oil Products	361	(30)	211	(11)
Natural Gas	111	(9)	130	(7)
Electric Energy *(1)*	152	(13)	182	(9)
Nuclear Energy	66	(5)	678	(34)
Total	**1210**	**(100)**	**1961**	**(100)**

(1) It includes: hydroelectric, geothermoelectric, other renewable energies

Against figures shown in the above tables the PV electricity generation in EU countries in 1993 amounted to about 0.5 TWh/year which corresponded to about 0.003% of annual European electric consumption, and was enough to supply about 0.05 million people.

All the considerations above show that a new approach is necessary to break the «chicken-or-egg» syndrome.

Considering, for example, the Italian situation, electric energy consumption in 1992 was 245000 GWh, an increment of 3900 GWh (+1.6%) compared to that of 1991.

Supposing an average annual growth of 1% (±2500 GWh) of RES, of which 3/5 mini-hydro, 1/5 photovoltaics, 1/5 eolic, a PV increment of 500 GWh/year, i.e. 500000 MWh/year, should be achieved. Since in Italy electricity production from PV is about 1400 MWh/MWp installed, 350 MWp/year should have to be installed.

However this figure is beyond the scope of PV at present: in fact in Europe today, producers have a total production capacity of about 10 MWp/year/shift; working with more shifts they could satisfy requests up to 35 MWp/year.

Working at full regime for 10 years the European producers could produce, with the present production capacity, about 350 MWp. This would only be a token contribution to the energy sector, but it is very near to the objectives fixed by the CEU DGXVII, Altener Programme which foresees in 2005 only about 500 MWp installed in the whole of Europe.

This means that, at least up to 2005, grid connected PV plants will be only demonstrative and will not contribute to the effective production of electric energy.

The cost factor should also be considered, however, and therefore the discussion point is not so much about power production but about the cost of the PV-Wp against the Fossil Fuels-Wp.

An analysis of this comparison is given in Section 3.3 of this study.

Such an approach should not only take into account the percentage of energy contribution that photovoltaics can offer, but to make consistent progress towards photovoltaic market development and penetration with a consequent cost decrease, the PV actions should be coherently linked to the following main goals of the European Union:

- Employment Creation
- Economic Growth
- Environmental Protection

and photovoltaic plants should give a consistent contribution towards:

- Improvement of quality of life supplying primary needs where lacking
- Improvement of quality of life supplying extra secondary needs
- Easing the higher national electric demand during peak hours and the grid connection of terminal sites.

In this scenario the three main lines of action to be supported to give a consistent boost to the photovoltaic market towards a self sustained economy should be the following:

1) **New opportunities in the non-energy market** (not otherwise possible without PV).

   Such new opportunities exist in all those situations in which the National Electric Grid does not exist or where any other economically viable solution cannot be implemented for technical reasons.

   For example it is useful to remember the PV vaccine cold chain, the PV fire watcher, the PV water mains watcher, etc., in which the energy aspect is secondary to the improvement of the quality of life.

2) **Small is beautiful**, i.e. the development of small and distributed PV systems, through the incentive of the PV engineering and systems firms and the setting up of more of them.

Such firms should have the role of designing and marketing the systems, gathering all the necessary equipment to make each specific plant, to install them and to carry out the after sales services.

There should be an incentive for new installations, fixing the goals that the firms involved should reach, i.e. improved B.O.S. components, etc.

In this approach the following photovoltaic systems have been considered:

- <u>Fixed PV distribution</u> (mainly to contribute to National Electric Grids during peak hours)

  - Photovoltaic roofs

  - Platform shelters, etc.

- <u>Mobile PV distribution</u> (mainly for extra secondary needs and health emergency situations not otherwise possible)

  - Calculators

  - Televisions

  - Refrigerators

  - Mobile medical units

3) **Big is necessary** to contribute to National Electric Grids during peak hours. It is necessary to sustain the market with demonstration plants of suitable dimensions to monitor step by step results of research into new PV technologies in which high investments are necessary. In such cases the following constraints apply:

   a) The plants should be completely supported by National Electric Institutions or by ad hoc legislation.

   b) The plants should all be grid connected to minimize the passive costs eliminating the storage.

   c) The orders of the Electric Institutions to the producers should be distributed over the year as a function of their production capabilities.

d) R & D support should in parallel be ensured by National and International Bodies such as Ministry of Industries, Ministry of Scientific and Technological Research, EU etc. to overcome “bottlenecks” in the PV production process and reduce production costs.

Today PV modules which are employed in power plants are produced using crystalline silicon (x-Si) as the active material. The two forms are monocrystalline (cr-Si) and polycrystalline (poly-Si).

Technologies based on other materials have been studied for many years without reaching the technical and economic results which would make industrial production of such PV technologies viable for electric power generation.

In fact industrial production of PV modules can be achieved only if the technological process responds to the following requirements:

- Reliability of the parameters which regulate the process
- Reliability of technological equipment
- Well known process efficiencies in agreement with the materials cost.

In the x-Si technology the above requirements, which are the obvious requirements to start any industrial production, are achieved, albeit with difficulty, whereas as far as the other active materials are concerned these requirements are not met at all.

From the above considerations the assumption below logically follows:

to achieve the "Altener" objective of 500 MWp in the year 2010, the industrial processes based on x-Si technology are the only viable solution.

However, existing PV production plants are only running at 50% of their production capacity and it is questionable whether PV producers, in the circumstances, could invest in new production capacity today, even taking into account the promising new technologies.

The technology of x-Si modules cannot be considered completely developed. Considerable improvements are in progress both at the conversion efficiency level and at the process engineering level. It is this second aspect in particular which will allow x-Si technology to achieve the cost objectives needed for the year 2010.

In chapter 2 of this study it will be demonstrated that the conditions exist to develop a manufacturing technology of x-Si PV modules with an industrial cost of about 1.8 ECU/Wp for PV production volumes of about 10 MWp/year/shift and with a conversion efficiency of 128 W/m^2 for poly-Si modules and with the same solar cell structure used today.

This will show that it does not follow that new devices necessarily have to be used; it is sufficient to introduce more updated manufacturing systems which allow an increase in the production rate of the existing process lines from about 0.15 m^2/min. up to about 1 m^2/min.

Since these rate increases do not imply device changes, they could be gradually introduced in the existing production lines. The results achieved would be proportional to the investments. Therefore a great investment for new completely different process lines would not be required as these might naturally occur in the case of new PV technologies.

In section 3.1 of this study an analysis of such new technologies is carried out. This includes some considerations about their development and incorporates some elements of costs.

The producers of PV modules are today facing a market situation which is dominated by the consumer. The PV modules prices are around 3,5 - 4 ECU/Wp - values very near to the industrial production costs.

The Gross Operating Margin does not exist at all or in some cases is a negative value.

The current production methodology alone cannot create an economic margin able to support the necessary technological development to achieve the objectives fixed for the year 2010.

Such developments must therefore be supported by contributions from EU (Joule, Thermie, Altener), National Governments, National Electric Institutions, the PV industries owners Groups themselves, etc.

To be wholly effective, it is necessary that commercial actions should be completely separated from R&D actions and that any support for R&D should go strictly towards R&D

activities; commercial activities should be completely financed by National Electric Institutions whereas R&D actions should be financed by the other bodies mentioned above.

It is also essential that commercial actions and R&D actions are completely separated and differentiated in the firms financial statements. This does not always happen, particularly if the commercial activities create some problems in the accounts, but it could be achieved with the creation of appropriate cost centres. Frequent Audits could help to discourage improper accounting practices.

The effect that intervention can have on the PV market at world level is presented in the following illustrations, at a quality level.

The aim of this study is to quantify such a quality approach and to find policies and tools capable of inducing the accelerated production scenarios.

The illustrations demonstrate that a completely "hands-off" approach - withdrawing national and international financial support from programmes - would result in some initial decline of the present market followed by some limited growth as the truly commercially viable markets develop.

Following investigations of the effect of the different intervention options, it would appear that a targeted approach using the existing level of public funding could accelerate the market.

Obviously though, increased, carefully targeted public funding for PV (following the application of the market development model) would have the greatest impact in accelerating the market.

The cost benefits of PV induced interventions can be used to assist in the development of a European PV strategy.

Benefits can be considered with respect to:

- avoidance of CO_2 emissions
- employment generation (through application of PV in Europe of increased exports arising from cost benefits of increased levels of production)
- energy diversity and security.

It should be noted that some intervention policies such as a carbon tax on power generation can generate income to public funds whilst encouraging the application of PV (and other renewables).

The three lines of actions mentioned earlier need to be supported to promote PV market development. These represent the tools needed to induce the gap introduced in the quality approach above between the business as usual curve and the targeted and accelerated scenarios curve together with the incentives to R&D activities for crystalline and new PV technologies which represent another necessary and equally important tool.

In this respect the financing bodies should:

a) Establish budgets and measures for each line of activity presented above. Envisaged measures for the line of action (3), “Big is necessary”, could be case studies in which to analyze feasibility of large PV plants in EU countries.

b) Define precise goals which the European PV industries should reach in terms of module delivery times, higher efficiencies and cost reductions.

c) Define precise goals for the PV engineering and systems firms for installed kWs.

To establish such goals in a way to be realistically achieved by PV producers and PV engineering and systems firms it is necessary to carry out the microeconomic analysis of the PV production process. A widely used PV production process is finely analyzed in chapter 2 of this study.

In this study all the issues outlined in this chapter will be reviewed more closely and analyzed together with these other aspects:

- PV production process: sensitivity analysis
- PV-kWh cost: sensitivity analysis
- Social costs of the traditional electricity generation and PV-kWh "credit"
- Crystalline silicon technology: technical improvements
- Immission of PV in the electric grid
- Cost and volume goals needed to reach the general competitivity
- Evolution of the polysilicon PV module cost
- B.O.S. cost considerations and improvement

2. THE MICROECONOMIC AND SENSITIVITY ANALYSES OF THE PHOTOVOLTAIC PROCESS: ITS ECONOMICAL INVARIANTS AND ITS COSTS

2.1 PV MODULES PRODUCTION TECHNOLOGIES

Currently the photovoltaic modules used for electric energy production are built from crystalline silicon (x-Si) as the active photovoltaic material.

Thin film modules are also built at demonstration level but reliable technical-economic evaluations are not available and in any case not suitable for the purposes of this report which takes into account only processes effectively used at the industrial level.

In chapter 3 of this study the state of the art of technologies other than crystalline silicon will be considered.

The evaluations in this chapter refer to the production of x-Si modules both in the monocrystalline and polycrystalline form, which as has already been stressed in the introduction, are the sole technologies able to respond to the necessary requirements for an industrial process i.e.:

- Reliability of the parameters which regulate the process
- Reliability of technological equipment
- Well known process efficiencies in agreement with the materials cost.

In reality, it is not yet clear which of the two forms is the most suitable for decreasing production costs. An additional purpose of these considerations, therefore, is to examine the problem from this point of view.

Analysis of large PV power plants shows that the major cost of such installations is attributable to the PV modules which account for about 50% of the total cost of the plant. The remaining 50% is attributed to the so called "Balance of System" (B.O.S.) component.

Published results of the "ELIO 1" plant in Italy for example, built by ANIT Srl, show that PV modules cost account for 53.5% of total plant cost, the rest being distributed among other components of cost as graphically illustrated hereinafter.

A detailed analysis of the PV module production process is therefore necessary to see where and which “bottlenecks” can be reduced or avoided to cut down costs.

The word “cost” in this study refers to industrial cost and therefore does not reflect the PV price.

Nowadays the relation between cost and price is quite casual because the industrial sector is not quite mature, in fact the entire production process is still considered an experimental and demonstration sector and not a business opportunity yet.

The current module price of about 3.5 ECU/Wp does not cover trading expenses. This implies that PV producers, as already mentioned in the previous chapter are accumulating losses.

The study was carried out with the data available between June and September 1994.

It is obvious that the general methodology introduced has a general validity and the interested reader can use it for several scopes using the updated values of the various parameters involved in the methodology itself.

The exchange rate used throughout the study was 1 ECU = 2000 Liras and $/ECU = 0.8.

Considerations on the B.O.S. improvements can also be found in this chapter, accounting for a high cost component.

2.1.1 Process Flow Chart

To produce crystal silicon modules, both monocrystalline and polycrystalline, it is necessary to use a series of technological processes very different from each other, as far as the industrial technology is concerned:

a) Preparation of the crystal (mono and poly) to start from the prime materials

These are operations with a metallurgical character which need high investments, knowledge of the chemical-physical field and operations at a continuous cycle.

This phase comprehends the feedstock preparation to start from the prime material (Solar Grade Silicon, S.G. Si) and requires to be discussed in detail in a separate paragraph in this report (see paragraph 2.4.5).

In the discussion of the flow chart given in **Figure 1** the starting point is the feedstock crystallization; this is a by-product of the silicon manufacture for an electronic use (Electronic Grade Silicon Scraps, E.G. Si-Scraps).

The available quantities of such a material is estimated around 2000 ton/year (see Figure 14 in this report), i.e. it is sufficient for a production of about 100 MWp/year when the whole actual market is around 60 MWp/year.

The price of such a material is around 8 ECU/kg.

In the present report the hypothesis to use E.G. Si-Scraps as feedstock is considered.

b) Silicon ingots cut into Si-substrates

This is an operation of mechanical type which requires a specific knowledge in mechanical engineering, particularly qualified operators, high investments.

c) Transformation of the substrates in solar cells

This is a phase of the work which shows several analogies with the sector of electronic components which requires specialistic competencies, particular attention to the technological details, moderate investments in respect to phases (a) and (b) above, automatic processes with a strong control of the operating parameters.

d) Assembling of the solar cells in modules

This is an operation with a technological content lower than the preceding phases.

The result depends more on the work accuracy than on the specific competence.

The requested investments can be low in view of the fact that the automation level is determined by the whole saving and not by process needs.

2.2 PRODUCTION COSTS EVALUATION OF MONOCRYSTALLINE AND POLYCRYSTALLINE SILICON WAFERS

To obtain economical evaluation it is necessary to look in detail into the single phases.

The analysis will be carried out with the following criteria:

- Within each phase the manufacturing process characterized by specific machines are identified.
  For each specific machine the following is determined:
  - the flow of materials which are necessary to the transformation of the product which enters a certain manufacturing process from the product which goes out;
  - the work necessary to obtain the transformation;
  - the investments related to the building and to the technical immobilization;
  - the energy consumption;
  - the efficiency with which the transformation is obtained.

  A specific cost correspond to each of those items and it is the transformation cost related to the manufacturing process considered.

- The transformation costs of each manufacturing process will determine the cost of the product of each single phase.
  For each phase the supervisors costs are calculated and the overheads are added to the product cost

- The costs are calculated for a "basic case" and then the influence of the various parameters is analyzed purposely disrupting the "basic case".

2.2.1 Determination of the "Basic Case" and Analysis of the Wafers Production Process

As "basic case" the production of polycrystalline silicon is considered. The polycrystalline silicon is prepared by directional solidification in crucible.

This method is followed because it is nowadays widely used in Europe (Photowatt, Bayer, Eurosolare, Crystalox) and also because it can be furtherly improved as far as the wafer area and its thickness are concerned.

The crystallization furnaces are nowadays able to produce ingots of polycrystalline silicon having dimensions 53 cm x 53 cm x 23 cm for a weight of 150 kg in a cycle of about 50 hours.

The cycle takes place in an automatic way and this is such that a single operator is enough to control 6 furnaces. This consideration determines the dimensioning of the Crystal Growth Department.

Hereinafter phases of the wafers production process are analyzed as follows:

- **Phase a) - Crystal Growth Department**
- **Phase b) - Wafering Department**

together with an analysis of the wafer cost.

Phase a) - Crystal Growth Department

The scheme of this department is illustrated in **Figure 2**.

There are four work stations.

Station n° 1 - Silicon selection

In this station the E.G. Si Scraps (in most part they are heads and tails of CZ ingots, but other waste from different working cycles can also be used) are selected according to their electric sign and therefore are classified according to their resistivity.

The "sign selection" is carried out by means of the Seebeck effect and therefore the scraps are subdivided into type "p" material and type "n" material. The type "p" material is then classified according to its resistivity by means of a four spikes measure.

As the final ingot should be type "p" with a resistivity of about 1 ohm · cm, the classification will be done in the following way:

- Type "p" a) $0.5 \le \rho < 1$ ohm · cm
  - b) $1.0 \le \rho < 3$ ohm · cm
  - c) $3.0 \le \rho < 5$ ohm · cm
  - d) $5.0 \le \rho < 10$ ohm · cm
  - e) $\rho > 10$ ohm · cm

Also type "n" material can be used, but with a $\rho > 3$ ohm · cm, otherwise the final ingot could result disomogeneous in resistivity.

Station n° 2 - Crucible preparation

The characteristics of the ingot are strongly dependent on the crucible in which the feedstock is melted and where the directional solidification takes place.

A proper preparation of the crucible is essential to obtain useful ingots.

They are crucibles in syntherised amorphous quartz obtained by slip casting. Because the melted silicon attacks the quartz, this sticks on the silicon and during the cooling phase, because of the different thermal expansion coefficient of the two materials, strong tensions arise between quartz and silicon. The result is that the ingot breaks and it becomes useless.

To overcome this problem a "varnish" based on silicon nitride ($Si_3 N_4$) has been developed. This acts as a separation layer between quartz and silicon.

The varnish preparation, its deposition on the crucible internal walls and the "cooking" to eliminate the solvent are all very delicate operations. Therefore the station is made of a chemical bench to prepare the varnish, a varnishing bench and a drying furnace.

Station n° 3 - Silicon feedstock cleaning and charge preparation

The selected silicon coming from station n° 1 is attacked by an alkaline solution to remove the surface impurities; the charge is then neutralized with chloridric acid and finally washed carefully using deionized water.

The silicon is then perfectly dried in the furnace.

To prepare the charge to the selected and washed silicon a certain amount of "mother alloy" is added. This is a silicon strongly doped with boron with $\rho \approx 10^{-3}$ ohm · cm.

The quantity to be added depends on the sensitivity and on the electric sign of the selected silicon used.

The type of the charge is also relevant in respect to the results; generally pieces of about 1 kg are positioned first in the crucible, being careful not to scratch the crucible surface and then the holes are filled with silicon of smaller sizes. The crucibles are such to accept up to 170 kg of selected silicon.

Station n° 4 - Crystal Growth

The charge is placed inside the furnace, on a support cooled with water. Inside the furnace the vacuum is made with two aims:

a) to eliminate every residual humidity,

b) to verify the good working conditions of the instrumentation.

The charge is heated and inert gas is put into the furnace to melt the charge completely.

The crystallization cycle is therefore initiated. This takes place under a twofold effect of a gradual cooling of the chamber and of a lowering of the charge by means of the cooled support, from the heated chamber to a not heated area of the furnace.

For a 150 kg charge the crystallization cycle has the overall duration of about 55 hours. Because 335 days available in a year are considered for a total of 8040 hours, each furnace will be able to make 146 cycles/year. It is necessary, nevertheless, to consider times necessary for maintenance and possible failures.

Therefore the analysis considers a furnace use coefficient of 0.8 and consequently 117 useful cycles per furnace.

The economic analysis of Crystal Growth Department is shown in **Table 1** (definition of the "basic case") and in **Table 3** where the results related to the "basic case", whose hypotheses are indicated in Table 1, are shown.

For comparison in Table 3 the results are also given for the preparation of monocrystalline silicon according to the Czochrolski method (CZ pulling) on the basis of the hypotheses shown in **Table 2** which takes into account the same quantity of product (≈ 100000 kg/year).

Discussion of the Analysis

The "basic case" takes to a cost of the crystallized silicon of 27.67 ECU/kg for a production of 100320 kg/year.

54% of the above cost is due to consumable materials which can reach 62% if electric energy is included.

Personnel cost represents only 10% of the total cost.

The process is therefore a "material intensive" process with a result which does not change much with the variation of the production volume. In fact to a doubling of the volume only a 8% cost decrease is obtained.

It is therefore clear that to improve the result it occurs to work on the process yields rather than on the volumes; the process yields depend on the operators capacity, they should be motivated and sufficient in number.

Supposing to increase the material yield from 0.86 to 0.95 the cost of the crystallized silicon would decrease from 27.67 ECU/kg to 25.04 ECU/kg with an annual saving equal to the wage of 6 operators.

In other words the factor process yield is very important in the determination of the product cost and the maximum effort should be made to constantly improve the process yields.

The comparison between monocrystalline and polycrystalline silicon for the same quantity of product is interesting.

The higher cost of monocrystalline product (about the double) depends on the higher cost of energy, which weighs 22% of the total cost against 10% of polycrystalline silicon, on the higher cost of the plants (23% against 16%) and on an higher consumption of chemicals (gas etc.).

All the above is the consequence of the lower quantity of ingot which every furnace can produce (≈ 1 kg/hour in the case of CZ against 3 kg/hour of polycrystalline silicon) and of the higher energy content of CZ silicon (175 kWh/kg against 25 kWh/kg) which is due to the more difficult management of the liquid-solid interface equilibrium.

Phase b) - Wafering Department

The flow chart of the wafering department is shown in **Figure 3**.

Three working stations are needed to transform silicon ingots in qualified wafers.

Station n° 5 - Cutting of silicon ingots in blocks

The silicon ingots should be cut in blocks of 10 cm x 10 cm section in the "basic case".

Because the ingots have a side of 53 cm, from each ingot 25 blocks of about 23 cm height can be obtained.

This operation which is made by a circular diamond blade implies a loss of material equal to 0.89 (shaping yields).

Measurements of the life-time of the minority carriers have shown that not all the material has the necessary characteristics ($\tau > 3\ \mu$ sec) to be used.

The parts in contact with the crucible have insufficient characteristics for a depth of about 1.5 cm, while the upper part of the ingot, even if not in contact with the crucible, shows a zone deep at least 1.5 cm with a low τ.

Near the corners the contaminated area is even deeper. Therefore from a single ingot 21 blocks of 20 cm height and 4 blocks of 15 cm height can be made.

So from a ingot of 150 kg 111.8 kg useful are obtained, with a metallurgical yield equal to 0.74. If a process yield of 98% is considered an overall yield of 72% is obtained.

Station n° 6 - Silicon blocks wafering

In this station the blocks coming from the preceding station, which have an height of 200 cm and a section of 100 cm^2 in the "basic case", are installed coupled over a glass plate in such a way to form two adjacent parallelepipeds 40 cm long, so that each cut run will slice

40 cm x 2 x 100 cm^2 x 2.33 g/cm^3 = 18.6 kg of silicon.

This load is sliced by means of a wire saw with a 0.04 cm/min feed. Because the wire has a thickness of 0.018 cm, to obtain wafers of 0.035 cm it is necessary to maintain a pitch of 0.055 cm, having considered a further tolerance of 0.002 cm.

Therefore a cut operation produces

80 cm/0.055 = 1454 cuts in 10/0.04 ≈ 4.2 hours

to which before starting the successive cut at least 1 hour should be added for a total of at least 6 hours.

Therefore a single saw has a theoretical capacity of

335 days x 24/6 hours = 1340 cut cycles

Nevertheless the saws need frequent maintenance and cleaning operation so that an availability coefficient of 0.8 is considered and so the effective cycles are 1072.

Therefore in the above conditions the overall capacity of a wire saw is

$$1072 \text{ cycles} \times 1454 \text{ cuts/cycle} = 1445688 \text{ cuts} \times 0.01 \text{ m}^2\text{/cut} =$$
$$=15590 \text{ m}^2\text{/wire saw/year}$$

Because the blocks to be cut coming from the station n° 5 are 70224 kg

$$70224/18.6 = 3775 \text{ cycles} < 4 \text{ wire saws} \times 1072$$

will occur.

Four wire saws are therefore necessary. These would require 2 operators per shift for a total of 8 operators.

To make the cuts it is necessary to prepare a mixture of "cut oil" and silicon carbide.

Extra costs derive from the disposal of the cut wastes with a cost evaluated in 2.5 ECU/kg of silicon to be cut.

This operation is very delicate: the material yield is only of 0.605 and its value in weight increases of 172%. Banal operative errors could induce serious economical damages.

Station n° 7 - Wafers separation, qualification and packing

The preceding station produces blocks cut with the wafers still anchored with glue and glass substrate.

This station has the task to detach the wafers from the substrate, and always with chemicals, to separate the wafers amongst themselves, to take away oil and abrasive, to wash them in deionized water, to dry them, to eliminate those imperfect and finally to pack them up and to send them to the warehouse.

They are mainly manual operations which carry out also a final control to eliminate every wafer which shows some metallurgical or cut problems.

The equipments are chemical hoods with some automatic auxiliary products and centrifuges to dry the wafers.

The summarized data of the wafering department are shown in **Table 4** both for monocrystalline and polycrystalline silicon.

Also for this phase the consumable materials represent the most part of the cost (more than 70%) if input material is included.

It is confirmed that the most important point is to maintain the operations control so to eliminate every error cause. The majority of the losses can be attributed to a non optimal management of this department. An increase of the production quantity will have beneficial effects on the costs only if overall yields will improve as much as the volume increase.

The costs of the cuts are nearly equal both for monocrystalline and polycrystalline silicon (53.2 and 57.6 ECU/m^2 respectively).

Because the monocrystalline material is more expensive, a bad management of this department will have for this reason more negative consequences; on the other hand an improvement of the process yields will be higher for monocrystalline silicon.

An increase of the production volume causes only marginal effects on the cuts cost, because all the items of cost are practically proportional to the cut surface.

2.2.2 Analysis of the Wafer Cost

Important conclusion can be obtained putting together in a sole department all the operations which take to the wafer, i.e. the Crystal Growth Department and the Wafering Department are considered together to identify the items which make the wafer cost.

Such a calculation both for monocrystalline and polycrystalline silicon is shown in **Table 5**.

Consumable materials represent respectively 39% and 50% of the cost and it is confirmed that the wafer production implies "material intensive" processes.

The electric energy represents in the two cases 16% and 6% of the cost. These values are important for monocrystalline silicon and not negligible for polycrystalline silicon and they cannot be decreased.

Furthermore it is known that the energy contents of the wafer (excluding the feedstock) is 270 kWh/m^2 for monocrystalline wafer and 70.3 kWh/m^2 for the polycrystalline wafer.

Totally the manpower represents 15.2% and 18.5% of the respective costs; to produce 47000 m^2 it is necessary to have 24 people of whom 21 operators distributed over three continuous shifts in the polycrystalline case and 30 people in the monocrystalline case.

The depreciation rate of the plants (7 years) and of the buildings (15 years) contribute 12% for polycrystalline silicon and 18% for monocrystalline silicon.

In the case of polycrystalline wafers, to those depreciation rates corresponds an investment of 4.3 Millions ECU for technical fixed assets and 0.6 MECU for industrial buildings for an overall under roof area of 780 m^2.

For monocrystalline wafers the above values become: 9.73 MECU for equipment and 0.75 MECU for industrial buildings for an equipped area of 1000 m^2.

Overheads were calculated to the amount of 80% of the labour cost. These cover for the cost of personnel management, maintenance, purchases.

Finally the "basic case" determines a wafer cost of 116.5 ECU/m^2 (1.165 ECU/Wf) for polycrystalline silicon and 164.8 ECU/m^2 (1.58 ECU/Wf) for monocrystalline silicon.

Because of the incidence of the consumable materials it is an illusion to think that an increase of production capacity will take to a significant improvement of the production costs.

The process yields (monocrystalline = 0.77%; polycrystalline = 0.72%) and material yields (monocrystalline = 0.37%; polycrystalline = 0.32%) are very low; it is on this aspect that it will be necessary to work to decrease the wafer cost.

2.2.3 Sensitivity Analysis on the Wafer Production Cost

Production Cost vs Volume

It was several time stressed that, because of the high incidence of the cost related to consumable materials over the overall wafer cost, an increase of the production volume would have only marginal beneficial effects.

An example of this is given in Table 3 for the silicon ingots, where at the doubling of the production capacity, does not correspond a significant decrease of the production cost.

The same behaviour can be observed for the wafer production.

Finally an increase of the production capacity does not imply for the wafer cost an higher decrease than the "basic case".

Production Cost vs Process Yield

The process yields given in the tables can be classified in two categories:

a) Those deriving from technological aspects such as the shaping yields and the metallurgical yields of the ingots;

b) those deriving from statistical errors, from a misfunctioning of the equipments, from operation errors.

In the first case it will be possible to operate at a technological improvement level of the production processes and it will be discussed in the next paragraphs.

The type (b) yields depend on the reliability of the equipment, on the skill of the operators and on the overall production management.

In the "basic case" the overall material yield for the polycrystalline silicon is equal to 0.326 (Table 5).

The technological factors correspond to 0,74 (metallurgical yield) and 0.614 (material yield of the cut); the factors which depend on the control of the production system correspond to 0.718; if these improve for the effect of an improved management reaching up to 0.877, relevant improvements on the cost can be obtained.

This effect is shown in **Figure 4** where it can be seen that an improvement of 10% on the material yield can be found in a decrease of 25% of the wafer industrial cost.

Production Cost vs Wafer Thickness

It has been seen how much the material cost influence the overall cost of the silicon wafer.

Therefore a cost reduction is expected when the wafer becomes thinner and from 1 kg of silicon it is possible to obtain an higher number of wafers.

Obviously this is true if the process yields remain unchanged. The wire saws can cut without any problems wafers as thins as 100 µm, but the successive operations of collection and washing become more difficult when the thickness of the wafer decreases.

Furthermore when the thickness is less than 200 µm, the solar radiation is not completely absorbed and the efficiency of the solar cell decreases unless some care is taken to optically confine the radiation inside the cell.

In **Figure 5** the sensitivity curve related to the production cost vs the wafer thickness is given. The curve clearly shows that at a thickness decrease of 1/3 corresponds a cost decrease of 15%, due to the better use of the ingot.

Therefore the wafers thickness decrease is one of the most significant factors on which it is necessary to work for the decrease of the PV cost.

Production Cost vs Wafer Area

As it will be seen at the solar cell and module level there is an interest to increase the area of the unitary device.

This, on principle, is uninfluent as far as the wafer production is concerned, because the costs are proportional to the weight of the crystalline silicon and to the area of the cut surface.

In the case of monocrystalline silicon an increase of ingot diameter involves serious problems at technological level.

It is sufficient to consider that the pullers which produce ingots of 5" diameter cannot produce ingots of significantly greater diameters.

On the contrary in the case of the polycrystalline silicon the starting ingot has much greater dimensions than the blocks which are used and therefore it can be hewed in the most suitable dimensions.

It can be then evaluated if an increase of the wafer area could involve advantages also at cost level in the case of polycrystalline silicon.

The original ingot has obliged dimensions 53 cm x 53 cm x 23 cm; this can be hewed in 25 blocks 10 cm x 10 cm x 23 cm or in 16 blocks 12.5 cm x 12.5 cm x 23.5 cm or even in 9 blocks 16.7 cm x 16.7 cm x 23 cm with the same shaping yields.

But, while in the case of 100 cm^2 blocks it has already been said that the corners are influenced by the crucible contamination and the overall yield becomes 0.7, in the case of bigger blocks the contaminated part of the silicon still exists but it insists on a greater area.

At the device level the result is a cell of a lower efficiency than those made of more internal material but in any case usable and furthermore masked by the efficiency distribution which usually can be obtained.

Figure 6 shows the effects of the area increase n the wafer cost. As it can be seen a sensitive decrease is obtained when the wafer area increases from 100 cm^2 to 156 cm^2, whereas a further increase of the wafer area does not produce any significant effect.

It can be noted that from the points calculated in Figure 6 it is not possible to extrapolate intermediate values because they do not correspond to any real physical situation.

Finally it can be observed that the cost decrease of about 7% for wafers of 156 cm^2 is due to a better use of materials and only marginally to the advantages deriving from the lower number of "pieces" manufactured.

2.3 SOLAR CELLS PRODUCTION

The cost analysis of the solar cells is carried out with the same criteria used for the wafers, i.e. the process has been subdivided in working stations according to the flow chart given in **Figure 7**.

It is a very simple process, particularly indicated for large production, with average efficiencies in the region of 14.5% in the case of monocrystalline silicon and around 12.7% for polycrystalline silicon.

The production capacity is determined by the speed of the silk-screen process machines used for the metallization.

For wafers of 100 cm^2 the metallization pace requires 4 sec per "piece" and therefore 900 "pieces"/hr which in surface units becomes 9 m^2/hr.

The other machines which make the production line should be compatible with the above pace.

Therefore the diffusion of P will be carried out in a belt furnace to a predeposition of $H_3 PO_4$ by spry.

The production line has in this way a production capacity of 9 m^2/hr which within one year becomes

$$240 \text{ days x } 8 \text{ hours x } 9 \text{ m}^2/\text{hr} = 17280 \text{ m}^2/\text{year}.$$

This number could be multiplied by 2 or 3 depending on the shifts number.

Obviously, the increase of the shifts have the effect to decrease the product cost because of the amortization share out and the general costs because of a bigger production.

On the other side, because the consumable materials represent the major voice of cost and the interest in this report mainly lies in analyzing this aspect, the chosen "basic case" for the solar cells is calculated over a single shift.

Station n° 8 - Wafer etching

The wafers coming from Station n° 7 are chemically attacked to remove a surface layer being damaged by the cut operation in the case of monocrystalline silicon, and to carry out the surface texturization, essential in the monocrystalline silicon case, not useless in the case of polycrystalline silicon, because a percentage of the surface between 10 and 50% has grains oriented near the crystallographic direction (100) and therefore open to texturization.

The action is carried out in an automatic chemical hood where the wafers are at first attacked by an alkaline solution and after neutralized by means of HCl, rinsed several times in deionized water and finally dried in a spin drier.

Station n° 9 - Phosphorus diffusion

The wafers are automatically loaded in the predeposition chamber where a thin layer of $H_3 PO_4$ is applied to the wafers.

By means of a belt the wafers are sent to the chain furnace for the diffusion. This has such a temperature distribution to obtain a diffusion of the P for a thickness of 0.3 ÷0.4 μm and with a sheet resistance of 30 ÷40 ohm x square.

The diffused wafers are automatically collected in appropriate containers.

The operator in charge of this phase of the process should only supervise the perfect machines operations and can also take care of the next station, the "Plasma etching".

The chain of the furnace can house 4 wafers of 100 cm^2 in line at a speed of about 0.5 m/min.; therefore the production capacity is of 12 m^2/hr compatible with the 9 m^2/hr of the silk-screen printing machines.

Station n° 10 - Plasma etching of the wafers edge

The diffused wafers are stacked in appropriate containers and are put in the plasma machine (CF_4).

The ions F^- attack the silicon on the wafer edge until they remove the diffuse layer therefore insulating the front "n" from the back "p".

This action has negligible consumption and labour costs which are absorbed by the other stations.

Station n° 11 - Oxide Removal

During the diffusion process a thin layer of silicon oxide takes place (≈ 0.1 µm) which is an obstacle to the next metallization and should therefore be removed.

This removal happens in a "chemical hood" with solutions based on hydrofluoric acid and ammonium fluoride.

Practically the wafers are inserted (automatically) in PVF (Polyvinyl fluoride) containers, submitted to a chemical etching, rinsed with deionized water and dried in a spin drier. An operator is dedicated to these operations.

Station n° 12 - Front contacts

The front contacts are applied by means of screen printing. It is a compound based on silver which is dried at ≈ 150°C.

The machines are fully automatic and are able to deal with 100 cm^2 every 4 sec., with a capacity of 9 m^2/hr.

The silver compound has a cost of 400 ECU/kg which at the wafer level becomes 6.65 ECU/m^2 (0.167 gr/wafer).

Those machines are manned by 0.5 operator. The yield is 0.99.

Station n° 13 - Back contacts

The wafers with the front contact already dried, are back contacted still by screen printing.

The compound is an alloy of Ag and Al which has a cost of 250 ECU/kg and over every wafer of 100 cm^2 1.7 gr will occur, i.e. 41.75 ECU/m^2.

After drying of the back contacts, the wafers are taken to about 750°C to allow contacts to permeate in the silicon forming an alloy and allowing to have contacts with ohmic behaviour also with high currents, with a low resistivity ($\approx$ 10 m ohm).

Then in line with the screen printing machine and the next drier, there is the "firing" furnace.

The above is fully automatic and 0.5 operator is enough to man the station (i.e. one operator can man stations 12 and 13).

Station n° 14 - Antireflecting coating deposition

The antireflecting coating (ARC) is coated on the wafers through Chemical Vapour Deposition (CVD) of a titanium metallorganic compound. This, taken by a nitrogen current on the wafers which are dragged by a chain, at a temperature of $\approx$ 150°C, decomposes depositing over the cells a layer of $T_i O_2$ of about 0.08 μm able to interfere with the silicon surface.

The result is that the reflectance of the silicon is in this way reduced to 8% in comparison with the 30% of the bare silicon.

This phase is carried out with a chain furnace equipped with $Ti O_2$ diffusors.

The furnace capacities are greater than those of the screen printing machines. At the furnace output complete solar cells can be found.

Station n° 14 - Solar cells sorting

In this station the solar cells are measured for their electric performance, using a solar simulator, and subdivided by efficiency classes.

The efficiency is calculated at a prefixed tension (V = 0.484 Volts). This is therefore a current selection.

This operation is essential to assemble modules with solar cells of the same current, in this way avoiding a modules power decrease for electric "mismatch".

Because the polycrystalline material is rather disomogeneous in lifetime, efficiencies can be distributed in several classes. It is therefore necessary to establish what is the minimum acceptable efficiency, solar cells at a lower level should be discarded.

In the "basic case" the minimum efficiency is located at 11% and this implies a further loss of 3 - 4%.

2.3.1 Production Cost Analysis of Solar Cells

A line able to process both monocrystalline and polycrystalline silicon is assumed, both of them with a process yield in the "basic case" of 0.903.

Because the line is therefore able to build 1662000 pieces/year of 10 x 10 cm in a single shift, 16620 m^2/year of polycrystalline silicon and 15960 m^2/year of mono-crystalline silicon will be produced.

The evaluation results are indicated in **Table 6**.

Therefore it can be found that, for the solar cells production the process is materials dominated and therefore it is not possible to significantly decrease cost increasing production volume, not even increasing the shifts number.

On the basis of the data processed for the polycrystalline silicon in fact, working over three shifts, production could increase up to 49860 m^2 at a cost of 243 ECU/m^2 and therefore only with a 4% cost decrease.

Nevertheless the wafer department can produce 46860 m^2 and therefore could feed three shifts of the solar cell department.

More information can be obtained analyzing together the wafer department and the solar cell department, as shown in **Table 7**, both for monocrystalline and polycrystalline silicon.

It can be therefore found that the monocrystalline solar cell has a production cost of 20% higher than the corresponding polycrystalline cell.

The feedstock (E.G. Silicon Scraps) increases the cell cost of about 9%. This value added to the other consumable materials necessary to build the cell represents more than 40% of the overall cost.

The electric energy represents 5% in the polycrystalline case (128 kWh/m^2) and 11% (348 kWh/m^2) in the monocrystalline case.

In the case of polycrystalline investments of 3 MECU and ≈ 550 m^2 of equipped industrial area are needed to produce ≈ 16000 m^2/year/shift of solar cells from feedstock.

For the production of the same quantity of solar cells, but buying the substrates elsewhere, investments of 1.1 MECU and ≈ 220 m^2 of equipped area are needed.

In the case of monocrystalline silicon the investments to produce from feedstock are ≈ 4.8 MECU with an equipped area of ≈ 570 m^2.

The same investments and the same area of the polycrystalline case are obviously needed to produce only solar cells buying the wafers.

As far as the staff is concerned, 10 operators and 1 supervisor are necessary for cell production both in the monocrystalline and polycrystalline case. On the whole 40 people for monocrystalline and 34 people for polycrystalline are necessary to produce solar cells from feedstock.

Production over four shifts

The line is able to produce 16600 m^2 of solar cells over one year in a single shift (polycrystalline silicon "basic case"). If the same line at its maximum capacity could work 7 days/week, 24 h/day and for 335 days/year production capacity in this case would be of 70000 m^2.

To produce over 4 shifts 40 operators and 4 works foreman occur and their cost will increase of about 1/3 in respect of the daily operations. Also overheads will increase in a proportional way.

Therefore the cost is reduced to 248 ECU/m^2 with a decrease of only 2%.

This means that production over more shifts can only respond to a market demand but it does not reduce production costs.

2.3.2 Sensitivity Analysis on the Solar Cell Production Cost

Production Cost vs Process Yield

In **Figure 8** the percentage variation of the production cost is given as a function of the process yield. At an improvement of 1% of the process yield corresponds an equivalent reduction of the production cost.

It is necessary to take into account that to maintain the cell process yield over 90% is not simple in an automatic line. A possible target could be around 95%.

If wafers and cells are taken together, the impact of the improvement of the wafer process yields over the cells cost could be evaluated. This is shown in **Figure 9**.

Improving the wafer process yield, which in the "basic case" is very low (only 34%), of 6%, about 10% decrease of the cells cost is obtained.

It is therefore reasonable to insist on the improvement of the wafer yields to obtain a reasonable advantage also at cells level.

A similar effect is expected when the wafer becomes thinner. This is shown in **Figure 10** where, for the effect of a better material yield, a decrease of the wafer thickness of 100 µm, corresponds to a cell cost 7% lower than the "basic case".

Effect of the Wafer Area Increase over the Cell Cost

In Figure 6 it was seen that, because of the ingot dimensions, wafers of 100 cm^2 or 156 cm^2 or 280 cm^2 can be obtained depending on how the ingot is cut if in 25 or 15 or 9 blocks respectively.

As far as the wafer costs are concerned, a decrease of about 7% can be obtained, going from 25 to 16 blocks. No further variations can be detected below this value.

When those wafers become cells, it is observed that the running costs are practically the same, except for the consumption of serigraphic compounds, and that the serigraphic machines nowadays available can handle surfaces up to 400 cm^2.

Putting aside, for the time being, the question of the cell efficiency which is not negligible in relation to the wafer area, an increase of the wafer area means an increase of the line production capacity.

Leaving constant the serigraphic linear velocity and the loading and unloading times, the serigraphic velocity is 1 + 2 + 1 = 4 sec. for a standard 100 cm^2 wafer and becomes 1 + 2.5 + 1 = 4.5 sec. for a 156 cm^2 wafer and 1 + 3.3 + 1 = 5.3 sec. for a 280 cm^2 wafer and therefore the above values respectively mean 0.15 m^2/min., 0.21 m^2/min. and 0.32 m^2/min. All the above would not change significantly the structure of the process.

The result of the above analysis is shown in **Figure 11**. The relationship is not linear and the decrease is more evident for little increases of the area with a certain tendency to reach saturation when the area goes over the 300 cm^2.

Therefore the advantage to increase the wafer and cell area is particularly significant for little increases of the area, i.e. when the hypotheses done are justified.

These considerations are valid only for polycrystalline silicon cells because nowadays it is not feasible to vary the monocrystalline wafers area without increasing their costs.

2.4 PV MODULES MANUFACTURING COSTS

The assembling process of solar cells in PV modules is shown in **Figure 12**.

Even if the process is quite complex, in spite of what has been done in the case of wafers and solar cells, it will be analyzed as a single station.

The solar cells coming from station 15 have already been selected in efficiency classes.

The selection is effectively done measuring with a solar simulator the current photogenerated at a fixed tension (V = 0,485 Volts), therefore the cells are classified in current classes.

This is reasonable because, the module which will be assembled will be made of 36 cells in series.

This is the traditional shape of the PV modules because 36 cells in series are able to charge a standard Pb battery.

Through soldering (using a Sn/Pb alloy in this case, but it can be also done by ultra-sound), a buss bar of nickel plated copper is applied on the front grid of the cells exactly in correspondence of the two buss bars.

The buss bars will connect the front of the cells with the back of the successive series.

This operation is done by means of an automatic machine which is able to tab about 300 cells/hour, with a cost of 50000 ECU.

The tabbed cells are put over a template upside down so that the tails soldered at the front are brought on the back of the adjacent cell.

The whole system above is put into a stringing machine in which a welding heat head makes the link, being the template translated in respect to the head by means of an x-y table driven by computer.

This machine can solder strings of 9 cells and prepares 16 strings in 1 hour, which is equivalent to 4 modules/hour.

Always by means of the use of templates, 4 strings are manually assembled to make the cells array.

A "sandwich" is then prepared made of:

- a sheet of ethyl vinyl acetate (EVA)
- a cells array
- tempered glass with holes for output cables.

The sandwich is then put into a machine (laminator) which at first warms it up to 90 - 100°C, then vacuum is done and then it is pressed and taken to 150°C.

During this cycle, which takes about 45 minutes, the EVA sealing material at first softens and then encapsulates the cells array. In this action it compensates possible thickness discontinuities.

Then it releases all gases (air, solvents) because of the vacuum and then it polymerizes, forming a sealed package, perfectly transparent, stable to the U.V. radiation action.

The laminated module is finished applying around it a frame which has a double use: on one side it is the interfacing element between the module and the supporting structure and on the other side it allows the sealing of the laminated edge with a silicon bead, or with other sealing material which does not allow and oxygen and humidity to enter the material itself.

The electric terminals coming out the laminated side by means of special holes in the back glass are gathered in a junction box: this is overlapped to the output holes and contains the terminal box of the connection cables among several modules, possible by-pass diodes and string diodes.

The junction box is the electric interfacing element between the module and the external world. Also the box is applied to the back of the module by means of silicon adhesives.

The so finished module is therefore tested for its electric performance by means of an appropriate solar simulator.

Modules Department Dimensioning

The production capacity of the modules department depends on the feeding of solar cells.

It seems reasonable to match production capacity in the modules department with that of the cells because both can work over several shifts whereas the wafer department should necessarily work over four continuous shifts.

It has been seen that in the "basic case" (polycrystalline silicon) the cell department produces 16620 m^2 of cells over one single shift for 240 days/year.

The other physical data are:

- Modules, 36 cells in series, have an active area of 0.36 m^2, whereas the effective area is 0.36/0.85 = 0.423 m^2
  In the case of monocrystalline silicon cells the modules have an active area of 0.346 m^2, whereas the effective is 0.42 m^2.

- Each laminator could house 1.2 m^2 of effective area equivalent to three modules per cycle which has a duration of 45 minutes.

- Each laminator can produce 30 modules/days and seven are necessary to absorb the cell department production.

- Each tabbing machine can produce 300 pieces/h which, in the "basic case", means 3 m^2/h and therefore 24 m^2/d, i.e. 5280 m^2/y.
  In other words, it requires four tabbing machines to absorb the cells production.

- The stringing machines have a capacity of 32 strings/h and i.e. 8 modules/h equivalent to 5530 m^2/y; therefore four machines are required.

- The framing system and the solar simulator are certainly able to absorb the cell production.

- Needed personnel: (1 shift):

Tabbing	1		
Stringing	1		
Sandwich preparation	4	Supervisor	1
Lamination	1		
Framing	2		
Texting	1		

The cost evaluation related to the PV modules production is shown in **Table 8** both for monocrystalline and polycrystalline silicon modules.

Because equivalent values are added to the cell cost, it can be found that the cost gap between monocrystalline and polycrystalline silicon is reduced.

In fact according to this estimate the cost of the monocrystalline module is 395 ECU/m^2, whereas the cost of polycrystalline module is 349 ECU/m^2 with a difference of only 8%.

At wafer level this difference was 34% (Table 5) and it became 20% at solar cell level (Table 6).

2.4.1 Cost Analysis of PV Modules

It can be now calculated how the single departments, i.e. feedstock, wafer, solar cell and PV module increase the final cost of modules.

The result is shown in **Table 9** for monocrystalline and polycrystalline silicon. In this table the costs are referred to the modules square meters. It can be immediately seen that the transformation costs of wafers into cells and of cells into modules are equal for monocrystalline and polycrystalline silicon and that the feedstock cost increases only of about 7% in both cases.

Moreover it can be observed that in the three departments the transformation costs are approximately made equal to the amount of 1/3 each. This means that to decrease the module cost the same attention must be put to all the departments, even if, traditionally, many efforts are dedicated to the wafers and cells technology and very little is made to decrease the encapsulation costs.

Cost of module per voice of cost

If the module production is considered as a single department, the nature of the cost making the module can be identified.

It is in this way found, **Table 10**, that the major cost is represented by consumable materials (≈ 55%).

Labour represents 20%, general costs are 15% whereas 10% goes into depreciation.

Therefore if a business man decided to set up a PV module plant starting from the feedstock and based upon monocrystalline or polycrystalline silicon, for an annual production of about 18500 m^2, he should invest about 6.2 MECU in the case of monocrystalline silicon and 4.4 MECU for polycrystalline silicon, he should need ≈ 1000 m^2 and he should employ 43 operators, 4 supervisors and 2 manager.

The production cost would be of 395 ECU/m^2 and 349 ECU/m^2 for monocrystalline and polycrystalline silicon respectively.

The energy consumption is of 328 kWh/m^2 for monocrystalline and 122 kWh/m^2 for polycrystalline. Such values represent the energy quantity necessary to transform the required consumable materials in modules.

2.4.2 Module Wp Cost

Until now the modules production cost has been calculated without considering their conversion efficiency which obviously depends upon the nature of the used monocrystalline or polycrystalline material and upon the process type used to transform the wafers into cells.

The type process considered in Figure 7 is able to produce cells with an average efficiency of 14.5% using first rate monocrystalline material ($\tau > 10$ µsec) and of 12.5% with polycrystalline material of excellent quality ($\tau > 4$ µsec).

In the case of monocrystalline silicon the standard module with 36 cells in series, with an area of 96 cm^2, will have a power rate of 50 Wp upon an area of 0,423 m^2, i.e. ≈ 118.5 Wp/m^2.

Therefore the average industrial cost for this type of material will be

$$395/118.5 = 3.33 \text{ ECU/Wp}$$

Using the same calculation for polycrystalline module an average industrial cost of 3.28 ECU/Wp can be obtained.

2.4.3 Sensitivity Analysis of the Module Cost

Effect of the Wafer Thickness Reduction over the Module Cost

With reference to Figure 10, it has been seen that a wafer thickness reduction of 100 µm (as an example from 350 µm to 250 µm) with the same process yield, takes to a cell cost reduction of 7%.

Because the cost of the cell + wafer (see Table 8) represents 65% of the module cost, such a thickness reduction implies a decrease of 4.5%. I.e. if the module costs 349 ECU/m^2 with polycrystalline wafers of 350 µm, it will cost 333 ECU/m^2 if obtained with wafers of 250 µm .

Effect of the Wafer Area Increase over the Module Cost

This effect is shown in **Figure 13**.

It partly reflects the same behaviour shown for the cells (Figure 11). It also shows that increasing the substrate area useful advantages can be obtained also at the module level.

In particular the advantage is interesting for small area increases: an area increase of 20% (wafer 11 cm x 11 cm rather than 10 cm x 10 cm as in the "basic case") takes to a decrease of the module cost of 10%.

2.4.4 Comparison between Monocrystalline and Polycrystalline Silicon

The obtained results demonstrate that nowadays there are no reasons to prefer a material compared to the other. Even if the polycrystalline material seemingly gives a value lightly lower than monocrystalline material, this little difference can be compensated by the higher power density of monocrystalline which is positively reflected at photovoltaic plant level.

Nevertheless it is necessary to consider that the future developments will take advantage of the polycrystalline efficiency in terms of big area and material performance which can improve due to thermal treatments such as "gettering" and "hydrogen passivation".

Therefore it is possible that, at least for the moment, the two materials will find complementary specific applications: the monocrystalline silicon will be preferentially used where there are high plant costs linked to the area; whereas the polycrystalline silicon will be better used where the low module cost is preferred with respect to the available area cost.

The obtained values (monocrystalline silicon 3.33 ECU/Wp and polycrystalline silicon 3.28 ECU/Wp) are related to industrial cost only and therefore they do not take into account interest rates, marketing costs, research costs.

It is also difficult to evaluate the comparison between these calculated values and the final values coming from the real use of the production lines. Being the economic result strongly dependent on the process yields, it should not surprise if the real costs could exceed the calculated costs even more than 20%.

Finally, considering that the ongoing market price is ≈ 3.5 ECU/Wp, it is easy to understand in what difficulty are the PV module producers which are accumulating losses both in Europe and elsewhere.

2.4.5 Silicon Feedstock for Photovoltaics

All crystalline material used in the photovoltaic industry comes from the semiconductors industry under the form of off specifications polycrystalline silicon or under the form of heads, tails of off specifications monocrystalline silicon, coming from the pulling according to the Czochrolski method (CZ-Silicon).

It is a very pure material of electronic grade (E.G. Silicon) not to be used in the electronic industry because of dimensional reasons (heads and tails of CZ-ingots) or for crystalline structure defects (high dislocation density ingots, twinned ingots) or for an off specification doping concentration.

This material is collected by photovoltaic industries and remelted in CZ pullers as well as in Directional Solidification Furnaces for the growth of mono and polycrystalline silicon respectively.

This source of feedstock could be used also afterwards if the availability is sufficient and the price convenient, otherwise a different supplying source should be found, purposely studied for the photovoltaic application.

To understand the situation, it is necessary to ask and answer the following questions:

1) Which is the quantity of off grade E.G. Silicon today available and how this availability will evolve in the next years

2) At what price off grade E.G. Silicon is today available and how the price will evolve in the following years

3) If nowadays there are available processes alternative to the one which produces E.G. Silicon and at what purity grade.

4) At what cost such processes will be able to produce Solar Grade Silicon and with what volumes.

2.4.5.1 **Availability of "Off Grade" E.G. Silicon**

With a material yield of ≈ 33% (see Table 5) to produce polycrystalline wafers of 100 cm^2 350 μm thick which make 1.3 W/wafer, about 21.2 tons are required to produce 1 MWp.

According to Strategies Unlimited evaluations the PV module world market was 55.7 MWp in 1993 and the forecast for 1994 is approximately 64 MWp of which at least 90% is made of x-Si. This means that in 1994 about 1230 tons of off grade E.G. Silicon have been consumed.

On the other hand the polysilicon production in 1993 was of about 11000 tons and it can be assumed that at least 10% of this quantity is directly or indirectly available for the photovoltaics; this would mean that nowadays there is a good balance between available and used feedstock.

But it is evident that this analysis is too simple because it does not take into account the heavy arrival on the market of the European East countries both with wafer and also with CZ and polysilicon ingots.

An evaluation of the overall capacity of this origin is very difficult because it looks like the plants once used to produce E.G. Silicon for the internal market are now unused and available for the photovoltaic use.

This new fact has significantly changed the previous forecasts and it will be at least one year before the new situation will be exactly understood.

2.4.5.2 **Price of "Off Grade Silicon" Feedstock**

The price of the feedstock at present varies from 6 ECU/kg to 10 ECU/kg according to the quantities, and of the mix which could be accepted.

An average price of 8 ECU/kg could be obtained for large quantities of the best quality silicon, i.e. heads and tails of CZ ingots, p-type with resistivity ranging between 1 ohm · cm up to 10 ohm · cm and more, selected in classes of ± 1 ohm · cm.

There is not any obvious sign that in the next months there will be a shortage of such feedstock.

But the situation could rapidly change following a more receptive PV market as it has happened in the second half of 1994. Therefore in the next years the situation could change.

It is possible to foresee the following scenario:

- The capacity of the "occidental" polysilicon increases with a yearly rate of 5%

- The capacity of the "Eastern Europe" PV grade polysilicon is at least 1000 tons/year to remain constant during the next decade

- The use of the polysilicon will become more efficient gradually going to 12 tons/MWp for the effect of a better process yield and for the reduced wafer thickness up to 280 μm

- In the next decade the increase of the PV world market is at the yearly rate of 10% as in the last 3 years and therefore in 2005 the shipments will be about 180 MWp/year which should become ≈ 300 MWp/year in 2010 (it should be noted that these hypotheses are very conservative because an annual growth of about 10% can reach with difficulty the ALTENER objective of 500 MWp of PV installed within Europe by 2005 and it is completely insufficient to reach the target of the Madrid PV Group of 16000 MWp installed within 2010).

With these hypotheses in mind the graphic of **Figure 14** has been carried out, from which it can be seen that if an E.G. Silicon production growth at an yearly rate of 5% could be obtained, the breakeven point between feedstock available and feedstock used will be reached only in 2008.

The breakeven point is brought forward to 2004 if a zero growth for the E.G. Silicon production is assumed.

The prices of E.G. Silicon depend on the evolution of the electronic market and it is not easy to carry out reliable forecasts.

The only certain fact is that in the last decade the cost has decreased from 12 - 16 ECU/kg (1984) to 8 ECU/kg (1990) and then it has remained constant up to the present days (October 1994).

An increase of the cost is expected within 1 or 2 years under the double effects of an increasing demand and of the ending of the "Eastern Europe" effect.

The foreseen scenario is very conservative: as it has already been said with this one it is possible to reach the ALTENER target but not the TERES target and it becomes even worst if the target proposed by the Madrid PV Group is considered.

Only if the political tendencies will push towards these aggressive programmes there is not any doubt that the feedstock problem would arise as a limiting factor.

2.4.5.3 **Industrial Processes of Solar Grade Silicon**

In the past years the Solar Grade Silicon problem has been approached in Europe with a series of studies carried out by the most important photovoltaic companies.

Siemens, Bayer, Wacker, Agip/Eurosolare, Photowatt, Elkem have made a strong effort to set up, at pilot plants level, production processes of sufficiently pure silicon to be specialized for the photovoltaic use.

The results have been published and some conclusions can be formulated:

- Industrial plants for the production of S.G. Silicon require very high investments which would need a minimum production of 1000 tons/year to pay them off. This would mean about 50 MWp/year and i.e. a single plant would be able to supply the present world production.

- The production costs of S.G. Silicon are evaluated between 12 and 18 ECU/kg and therefore higher than the actual 8 ECU/kg.

- There is the possibility to use already existing plants to produce E.G. Silicon and to specialize them for the PV use.
  In this way a certainly effective product can be obtained for the PV at costs which are lower than the normal E.G. Silicon (30 - 40 ECU/kg) because already paid off.
  Even if the cost rose to around 25 ECU/kg it would still be acceptable because the cost of the feedstock represents at present 7% of the cost of Wp and therefore its cost increase up to 25 ECU/kg could be absorbed by the other improvement factors (material yield, process yield, etc.).

3. MACROECONOMIC DEVELOPMENT TOOLS AND POLICY OPTIONS

The objectives fixed by the Declaration of Madrid are to achieve, by 2010, a 15% contribution of the energy required, from Renewable Energy Sources (R.E.S.).

This overall value has also been analyzed in the ALTENER Programme and the contribution of the photovoltaic electric energy was calculated at about 500 MWp installed in EU countries by 2005.

The purpose of this chapter is to estimate if this objectives can be achieved, what is the technology to be adopted, what are the costs and what are the financing and energy policy conditions necessary to the objective achievement.

3.1 TECHNOLOGY DEVELOPMENT STRATEGY

A century ago, when the electric power industry began, it was often difficult to distinguish electricity from the products that used it or from the comfort it provided.

For example, one of the United States industry's pioneers, Pacific Gas and Electric, began by selling lighting rather than electricity. Their first contract sales were for lumens of lighting, not kilowatthours of electricity.

Today's electric utilities no longer sell lumens of lighting. However, today's utilities customers, like their predecessors a century ago, still perceive electric purchases as purchases of services rather than of kilowatthours.

For example, a customer decides to "purchase" living room lighting at 10 PM, or pay for a cool house on a summer day, rather than explicitly deciding to purchase a given amount of electrical energy.

Therefore if available PV technologies do not make its use an attractive option as far as cost and reliability are concerned then customers will not choose it.

Three basic forces should be taken into account to make a consistent step forward in the PV market penetration: technology-pull forces, productivity-pull forces, and market-pull forces.

Each of this factors is explained below.

Technology-pull forces arise from technological innovations that increase the value of the technology. The enhanced value of the new end-use device is due to the greater satisfaction the consumer derives from its operation.

Productivity-pull forces occur when adoption of an innovation allows an increase in productivity.

Market-pull forces are principally consumer based and arise from the intrinsic economic utility of the end-use technology to its user. In simpler terms, market-pull forces are those forces responsible for product innovation, or the introduction of new products onto the market.

All three of these interrelated forces influence product adoption through their implications for product/service value.

Research and Development activities are typically focused on technology-pull factors that enhance the technological capabilities of an end-use technology.

Productivity-pull and market-pull factors are the principal determinants of customer acceptance of end-use technology.

In the previous chapter the productivity-pull forces have been deeply analyzed for the most nowadays reliable PV manufacturing processes, i.e. the crystalline silicon one.

In the next paragraphs the technology-pull forces as a review of the alternative technologies to crystalline silicon will be analyzed together with some consideration on market-pull forces and possible PV future trends scenarios.

3.1.1 Advantages and Limits of Crystalline Silicon (x-Si)

The x-Si is the more known and used semiconductor material. This is due to several causes such as: it is an elementary material and therefore with an easy control of stechiometry, it can be obtained at a very high level of purity, largely diffused in nature with an energy band gap Eg ≅ 1.1 eV which allows to obtain a theoretical conversion efficiency at AM 1.5 greater than 25% at ambient temperature.

It is therefore a material intrinsically steady, quite easy to be processed and able to reach high conversion efficiencies.

In fact the best laboratory cells have by now reached a conversion efficiency of 23% against the theoretical limit of 26%. This little difference gives a measure of the technological maturity of the x-Si.

For those reasons the x-Si is today the excellent PV material and it will remain as such for a long time.

But the x-Si finds a limit in its solar radiation absorption coefficient: to absorb 90% of radiation a thickness of at least 200 μm would be required, whereas only a few microns are sufficient in the case of other materials such as amorphous silicon (α-Si:H), CIS, CdTe, GaAs, which are in fact used in the thin film form.

Therefore the x-Si must be used in "bulk" form obtained cutting the ingots with material yield lower than 50%. This determines the "material intensive" aspect of the production processes of the x-Si modules and the high energy contents.

To overcome those difficulties, at least as a prospect, a certain number of options are followed at the Research and Technological Development level.

Of those above the most important characteristics are given here together with some considerations on the status of the art with medium and long term prospects.

3.1.2 Silicon, x-Si, in Ribbons and Sheets

A first way to reduce the wafers cost is to eliminate the cutting phase which affects the wafer cost for 48%.

The challenge is to achieve a growth method which could produce crystalline material at a pre-defined form (Shaped Growth).

After at least 20 years of attempts the actual situation could be resumed in this way: it is necessary to find the best compromise between ribbons geometric definition, crystalline structure, impurity content and production rate.

a) **Geometric definition**: To be used, the silicon sheet should have a thickness between 200 - 400 µm constant within ± 20 µm; this requirement limits the growth techniques to two possibilities: either the shape to be obtained is defined, making the solidification phase in a pre-defined space, and that is through a split (Mobil Solar, Bayer, etc.), or a silicon membrane is produced between two parallel silicon columns or other compatible material (Deudritic Web, Westinghouse).

b) **Impurity content**: Because of the high surface/volume ratio the pollution problems of the container are very serious and therefore either extremely pure materials are used which do not interact with the melted silicon (EFG, Mobil Solar and Bayer), or the contact with the growing material in the crucible is avoided (Deudritic Web, Westinghouse).

c) **Production speed**: The progress speed of the interface solid-liquid which determines, through the geometric form of the growing solid, the material production rate, depends on the system capacity to rapidly dispose the solidification heat, maintaining an high thermal gradient through the interface.
Such a capacity is little if the heat flows through the interface itself as it happens when the heat flow direction is parallel to the growth direction (Mobil Solar, Westinghouse) and it is very high when the heat flow direction is perpendicular to the growth direction (Bayer).

To increase the production rate, Mobil Solar makes the sheet growth to happen in 8 splits arrayed as an octagon obtaining some tubes long more than 1 meter with a prism form with an octagonal or ninegonal base, whose faces are easy to be separated with cutting actions. The production speed is in this way multiplied by 8 or 9.

d) **Crystalline structure**: In a first approximation the crystalline quality of the material seems to be inversely dependent on the growth speed. Therefore the best material with qualities very close to those of the monocrystal belongs to Deudritic Web, whereas that with the greater problems is the Bayer one.

Table 11 proposes a rough comparison among the different techniques to prepare Si-Ribbons.

It is nevertheless necessary to remember that Westinghouse has closed its activity in this sector and that at present Mobil Solar, now ASE, and Bayer remain in lists.

The growing technique developed by the latter, seems very promising because it has overcome the problems due to the geometric definition and to the production speed (> 1 m^2/min), but it has still to overcome the problems deriving from the low crystalline quality of the material.

3.1.3 Crystalline Silicon Thin Film Solar Cells

The need to decrease the material quantity has addressed many efforts to study devices able to effectively use very thin silicon thickness too. Therefore some laboratory techniques have been developed to treat the back surface of the cell.

Those techniques are such that the radiation with a greater wavelength, instead of going through the silicon cell, is reflected backwards, goes back through the whole material thickness and is again reflected from the upper surface. An optical confinement of the radiation is therefore obtained in 50 μm thickness too.

The treatment is even more effective if coupled to both superficial passivation which reduces the recombination of the photogenerated charges near both surfaces and a back surface field which speeds up the minority carriers towards the junction.

In this way solved, at least in principle, the problem to use a low thickness silicon, the problems to make it and to support it still remain.

Those aspects could be approached with the usual deposition techniques nowadays available which go from the Chemical Vapour Deposition (CVD) to the Liquid Phase Epitaxy (LPE) to the Solid State Recrystallization.

The major difficulties to be overcome are of two types:

a) the need to find a substrate compatible with the deposition material and as far as the physical-chemical aspects and as far as the economical aspects are concerned;

b) the essentially batch nature of those manufacturing processes with serious difficulties for the large scale production.

The substrates today used for this scope are ceramic, graphite, metals and silicon itself.

The economical type hopes are linked to the cost of the substrate much lower than the usual silicon wafer cost and at a process cost which would not cancel all the margin obtained at a substrate level.

In this sector the most significant results have been obtained by the American company Astropower. The used techniques is LPE over a ceramic substrate and the efficiencies obtained over a big area (225 cm^2) are almost 10%.

The development margins are high and the objectives are to obtain an average efficiency of 14%.

3.1.4 Amorphous Silicon Family

The properties of the hydrogenated amorphous silicon (α-Si:H) have been studied up to the seventies. Those include an high absorption coefficient for the sun light, the possibility to make a material with F_g which could vary from 1 eV up to 3.5 eV putting in the alloy together with the silicon other elements such as Ge and C.

Because it can be deposited at low temperature (between 100°C and ≈ 350°C) over several substrates (glass, metals, plastics, crystalline silicon) over very big areas, it can make heterojunctions and multilayer structures.

The manufacturing technology allows low cost and mass production. The production processes require little materials and therefore the product has a low energy content which allows a short pay back time.

Because of all those promising properties, the amorphous silicon and its alloys, Germanium and Carbonium, have been for years object of the greatest attention, also because they have had an industrial application in the pocket calculators, watches and similar consumer goods and gadgets supply.

The expectations were so good to persuade some industrial operators to set up production lines up to ≈ 1 MWp/year/shift much early in relation to the technical solution of the problems which still at present limit the modules performance based on α-Si and its steadiness in time.

In fact the laboratory efficiencies over a small area ($\approx 10\ cm^2$) are in the order of 12.5%, whereas at the 0.1 m^2 module level they decrease below 10%.

But the major problem is related to the steadiness of the device in time. In fact this refers to the so called steady efficiency, in this way meaning that the loss of efficiency in relation to the just made module, happens in the first hours of exposure and after it becomes steady.

Therefore the efficiency measure can be carried out after 600 h of exposure to the sun light at a temperature of 55°C.

After that the modules efficiency becomes 63% of the initial device efficiency in the case of a p-i-n structure and 75% in the case of a p-i-n/p-i-n tandem structure.

Furthermore it remains still to be demonstrated that the efficiency would remain steady over the years.

Recent results shown at the 12th European PV Solar Energy Conference held in Amsterdam, April 1994, p. 14 which refer to measures carried out over 5 years are not so reassuring: beside the usual initial degrade a long term degrade is clearly indicated evaluable at 3.5% within ≈ 5 years of exposure.

If this data would be confirmed, the life-time of the α-Si modules, evaluated in conformity with the x-Si modules, should be evaluated around 15 years against the 25 years of the x-Si.

Therefore it is possible to estimate a kWh cost originated from the α-Si modules on the basis of the evaluations which can be found in literature; those show a production cost of those modules around (2 ± 0.5) ECU/Wp for a production of 10 MWp/year and for a steadied modules efficiency of 5%.

In these conditions, the evaluation of the kWh cost carried out according to the modalities given in **Table 12** takes to 0.45 ECU/kWh, i.e. to a slight higher value than the "basic case" considered for the crystalline silicon.

It is therefore understood why, at the present state, the conditions to carry out investment on α-Si:H production lines do not exist if the problems linked to efficiency and steadiness are not solved before.

Prospects remain in any case interesting and because there are very good expectations to increase the efficiency, and because the production costs, being less linked to the material cost than those of the crystalline silicon, are more sensitive to the increase of the production volumes. The current estimations consider that a lower cost than 0.8 ECU/Wp could be reached with related fficiency of 10% and for production capacity over 10 MWp/years/shift.

3.1.5 Polycrystalline Thin Film

For this class of active materials, the comparison cost/performance with x-Si and α-Si:H cannot be done because none such type module has been really marketed.

Hereinafter some considerations over their prospects to be used in the future are given.

It must be said that the study of these materials is caused by the need to maintain the principal characteristics of the α-Si:H, i.e. the concept of a thin film device, the use of an Eg more capable than x-Si to absorb the solar radiation etc., eliminating in this way the efficiency and steadiness limits typical of the α-Si:H.

There are at the present time two families of materials which could in the future substitute the α-Si:H as the thin film photovoltaic material i.e. CIS and CdTe.

It is not possible today to say which one will be the winner, it is only possible to make some general considerations.

Stability

Both systems are steady and do not show the typical degrade of α-Si:H under illumination.
In relation to the x-Si the thin film based modules are more fragile because the hermetic level of the encapsulation is essential to keep the modules in good working conditions in time.
In the case of x-Si the effect of humidity and oxidation, is on the contacts but not on the material whereas in the case of thin films it is the material itself to interact with the external agents and the steadiness of these modules over the long term is not yet sufficiently known.

Efficiency

The efficiencies of the small area laboratory device are quite high and there is still margin for improvement if the theoretical efficiency is considered.

This is a very important point and in fact it has caused, very recently, a change of the research investments from α-Si:H to this class of materials.

Stechiometric control

Because of the complexity of the chemical-physical systems involved, it is obvious that the composition control both in chemical terms (stechiometric relations) and in physical terms (multiphase systems) is a serious problem for the process yield in the production lines.

The problem is accelerated in the CIS family where quaternary and pentanary systems are involved [Cu (In, Ga) (Se, S)$_2$] but it is not negligible even in the binary system CdTe where the conduction type depends on the excess and the defect of Te in relation to the stechiometric condition.

This implies the use of manufacturing processes with very narrow process parameters with an high probability to work off the accepted "window" to obtain usable devices.

Process yield

Because of what has been said before, and because the homogeneity of the deposition of layers as thin as only a few microns should be maintained over a large area, a not evaluable problem of process yield over production lines arises.

Even if in the thin films the material yields do not have as dramatic consequences as in x-Si, a serious indetermination, over real prospect of the polycrystalline thin films linked to the overall process yield, still remain.

Toxicity

Both families use elements considered dangerous such as Cd and Se. It should be probably said that this aspect should not be exasperated because a manufacturing process to produce modules could be carried out according to the present laws ensuring the safety of the personnel involved and the control of dangerous wastes.

The recycling problem of these elements, after the plant life-time, does not seem to be a problem because the quantities are very little in relation to the pollution caused by the same element (Cd) because of coal dust, varnishes, electrochemical batteries, etc.

Cd toxicity certainly represents an obstacle to PV modules development based of CdTe, but such an obstacle should find the most suitable technical solutions once their validity is proved also at the economical level.

Availability of In, Ga

For mass production of CIS modules the problem of the In and Ga elements availability arises.

The need of In in the CIS modules is of 6 - 7 gr/m^2 which, with an efficiency of 10%, takes to a consumption of ≈ 70 kg/MWp, when the present world In production amounts to ≈ 120 ton/year i.e. ≈ 1.7 GWp.

Even if a greater In demand could induce a greater production and the recycling techniques could increase its availability, the diffusion of these technologies could be limited by the In increasing cost.

3.2 TECHNOLOGICAL EVOLUTION

Having ascertained that crystalline silicon is the technology to be adopted, in this paragraph a possible technological evolution, starting from the analysis carried out in chapter 2 in this document, will be carried out.

The industrial cost of the Wp for modules made of crystalline silicon based cells, has a value of about 3.3 ECU/Wp with variations up and down according to the ability of the various producers to remain within the process yields indicated for the single process phases.

The minimum value of 1.8 ECU/Wp considered for the diffusion of the photovoltaic energy as primary source is still quite far to be reached. The problem of which improvement margins the crystalline silicon based technology has to reach this objective, should be wondered.

For each phase of the process the effects which the various parameters have on the product cost of the considered phase have been indicated.

It must be now examined, if and when and in which way significant improvements can be obtained for each single phase considering the limitations which the technology imposes.

It has been said several times in this document that the processes are "material intensive", i.e. the consumable materials costs are much higher than the other elements of cost. Therefore, the first aspect to be considered will be the improvement of the process yield. This means to have reliable process, safe and very little influenced by human errors. In other words, secure improvements can be obtained investing on process engineering rather than on the research of higher conversion efficiencies than those indicated.

Only after having established all the processes will be meaningful to improve the technological devices.

3.2.1 Wafer Cost Reduction

In Figure 4 the effect of the improvement of the process yield on the wafer production cost has already been shown.

It must now be analyzed how this is possible. The stations 1 and 3 yields cannot be improved a lot because the materials loss is intrinsic to the selection and washing processes.

The yield of station 4 depends instead on the machines reliability and on the operators ability. If with a good engineering the causes of malfunctioning can be eliminated, the yield can be taken to 0.97 from the value 0.95 considered in the "basic case".

In the station nr. 5, where it is necessary to eliminate all the low quality material, an overall yield of 0.77, rather than 0.74, can be obtained, improving the crystallization cycles and taking care of the crucible contamination.

In station 6, the yield strongly depends on the operators ability. It is therefore necessary in this case to improve the performance of the wire saws. If the technological yield in material is only 0.614 fixed by the wafer thickness (350 µm) and of the wire (200 µm) the process yield should be increased to 0.98 in comparison with the present value of 0.95.

Finally the yield of the station nr. 7, where all the defective wafers are discarded, should go from 0.9 to 0.95.

Therefore using simply a good management and a good engineering the wafer process yield in material can be increased from 0.326 to 0.4.

As it can be seen in Figure 4, this allows a cost decrease of 20% and therefore the polycrystalline silicon which nowadays has a cost of 116 ECU/m^2 (Table 5) could reach the value of 93 ECU/m^2.

The wafer cost decreases when its area increases. The improvement (Figure 6) it is not great (-7%) but it has a great impact both on the cells cost (Figure 11) and on the module cost (Figure 12).

It is therefore better to consider an optimum area of 12.5 cm x 12.5 cm in relation to the wafers process. In this case, keeping the same process yield of 0.4, for the 156 cm^2, a wafer cost of 86 ECU/m^2 can be obtained.

It is still possible to decrease the thickness. Nevertheless this change means deep modifications in each phase from the cut to the modules. In fact it is necessary to avoid that the thickness decrease determines a worsening in the process yield. To decrease the thickness it is necessary to achieve an automatic process of wafer collection, washing and drying.

Also at the cell process level it is necessary to improve the handling systems.

Therefore it is possible that, in a short time, the wafer thickness could decrease from 350 μm to 280 μm to be done on 156 cm^2 wafers.

From Figure 5 it can be found that this operation allows to decrease the cost of about 8%.

Therefore the 156 cm^2 wafer 280 μm thick will have a cost of 79 ECU/m^2.

3.2.2 Solar Cells Cost Reduction

The solar cell cost can decrease as an effect of the wafer lower cost, for an improved efficiency (obtained without increasing too much on the process cost and on its yields) and for an improved process yield.

This is today estimated around 90% and could go up to 95% with process engineering actions.

Therefore it is possible to evaluate which cost the solar cell should have with a yield of 95%.

Figure 8 indicates that with this yield the cell would cost 240 ECU/m^2. If instead the starting point is a wafer of 93 ECU/m^2 and that is with a wafer obtained with a 0.4 process yield, it can be found in Figure 9 that the cells cost decreases of 10% in comparison to the "basic case".

Finally the accommodation of the machines and of the management in both departments makes it possible that the solar cell would cost 226 ECU/m^2.

The increase of the solar cell area has a striking effect over its cost. Considering an area of 156 cm^2 (Figure 11) a decrease of 12% in relation to the "basic case" can be obtained and this takes the cost to 199 ECU/m^2.

A further decrease of 4% (Figure 10) can be obtained for effect of the decrease of the wafer thickness from 350 μm to 280 μm, taking the wafer cost to 191 ECU/m^2.

These considerations are shown in a graphic form in **Figure 15**.

It is useful to mention here that in Figure 15 and in the next Table 13 and Figures 17, 19, 20, 22, 23a) and 23b), the analysis was carried out to the year 2005 because this is the year expected to be the one in which it would be theoretically possible to obtain the technical and management results shown there, i.e. if the following will be satisfied:

1) Technical conditions: process yields, substrates dimensions and conversion efficiencies will be those really foreseen and summarized in Table 11 as far as the modules are concerned;

2) Management conditions: the producers will carry out in the foreseen time schedule the necessary investments to introduce in the production lines the described improvements.

Therefore is quite reasonable to expect a shift to the year 2008 ÷ 2010 to have the same result at a commercial level.

Because the area increase has a positive effect on the cells cost, a further increase could be thought.

But this finds a limitation in the need to collect very high currents which inevitably induce a lower conversion efficiency.

Supposing that this problem could be solved making cells over an extended substrate and therefore cutting them at the desired dimension, then it would be possible to make bigger cells (16.7 cm x16.7 cm = 278 cm^2) and then reducing them to more reasonable dimensions (16.7 cm x 8.35 cm for example).

In this case, always in the hypothesis to maintain the yields constant, a reduction of 18% in relation to the "basic case" could be applied rather than 12% and therefore the cost would be reduced to 178 ECU/m^2.

The effect of the efficiency improvement can be seen at the level of the Wp cost.

3.2.3 PV Module Cost Reduction

The modules process yield could easily increase to 0.98 with a few but effective actions.

On the other hand the cost of the module decreases because of the decreased cost of the wafers and of the cells.

It must be noted that when the wafer area increases the 36 cells module increases its area and its power rate. This has a meaningful effect over the module cost because some elements of the modules cost as such are now subdivided over a greater area.

The above considerations are synthetically shown in **Table 13** and graphically in Figure 15.

The first line of Table 13 gives the solar cell cost evolution which, because of the various actions described decrease to 178 ECU/m^2 from 253 ECU/m^2. The second line is the contribution of the solar cell cost in the module and therefore it is referred to the module area, considering a ratio cells area/module area = 0.85.

Therefore carrying out all the actions above indicated, the production cost of the module decrease from 349 ECU/m^2 to 239 ECU/m^2.

The cell efficiency and the consequent module power rate density, remain constant at the present value of 12.5% until the actions on the various processes are not carried out. Afterward the efficiency increases up to 15%.

The effects of the efficiency increase have therefore been separated from the previous ones because of editing reasons.

To obtain higher conversion efficiencies it is necessary to work on the quality of the polycrystalline material.

The present quality could reach 15% efficiency but it is quite disomogeneous and therefore the efficiencies distribution is quite wide and usually it has an average of 12.5% at the module level.

Experiments of "impurities gettering" by means of heavy diffusion of phosphorous and aluminium have been very effective in the improvement of the overall material performance, taking the average diffusion length of the lower carriers from 100 - 120 µm to 150 - 170 µm. With these values the average efficiency could reach 13.5%.

Further efficiency improvements could be obtained with actions to the cells process: surface passivation with oxide deposition, increases of the thickness of the serigraphic metallization, introduction of layers p+ at the back of the cells, could be able to take the efficiency to 15%.

Nevertheless these actions often make the process more difficult and increase the costs. It would be deceiving to think to make precise calculations introducing processes not yet stabilized in the methods and in the costs.

It is better to consider that those other costs are marginal in relation to what has been considered above and in any case they could be absorbed for the effect of other actions not described here, as for example the production volumes increase.

For those reasons the effects of the efficiencies improvement have been taken very far in time, when the production volumes should be more than triple than the actual one.

Therefore, in the last line of Table 13, the chosen dates in which the various actions could be taken to a successful end have been indicated.

Those dates represent only one possible time schedule, but many others could be chosen with different times. Probably, for example, efficiency improvements could be obtained in shorter times than those indicated, whereas the area increase up to 278 cm^2 could need longer times.

The fact that in the next period of ten years, the PV modules industrial costs could be maintained near to 1.8 ECU/Wp, certainly remain.

It is important to notice that to reach this aim there is not the need to foresee technological results which do not exist at present, but it is only necessary to do better what can already be done today.

There is not therefore any need to invest in new production processes but it is necessary to invest to give a more rational assessment to those already existent.

3.3 COMPARISON OF kWh COST: PV kWh COST vs FOSSIL FUELS kWh COST

PV electric energy has various applications each one with a specific cost. Frequently it is improper to speak of the PV-kWh cost because it is more interesting to know the use that the PV-kWh produces. For example, in the case of pumping, it is more interesting to know the cost/m^{3}of the water produced.

Furthermore if the user is not grid connected the PV-kWh cost should be added to that of other local factors. Therefore economic comparison are not simple and have to be considered case by case.

To carry out a comparison among costs, some parameters should be fixed:

- Since this analysis is concerned with the PV energy production in EU, it is opportune to consider PV plants connected to the national electric grid.

- Moreover the area of EU countries around the 40° parallel is considered as a strip of privileged application and to which an average annual insolation on the horizontal surface of 1500 kWh/m^2/year is attributed, flat PV modules which face south and 30° tilted over the horizontal surface are also considered, the ground cost is not considered because state property or marginal grounds are generally used.

  At this point it is possible to calculate the PV-kWh cost as a function of:

  - the average efficiency of the field at the average working temperature;
  - the cost of the module Wp;
  - the B.O.S. costs concerning both the area and the power rate;
  - the life-time of the plant;
  - the depreciation rate;
  - the plant power rate.

As an example in Italy for the 3.3 MWp ENEL plant in the Serre site, the total building costs are estimated to be around 40 MECU with a modules cost of 12 MECU and an estimated kWh cost of 0.4 ECU considering a plant life-time of 25 years.

Keeping the B.O.S. cost fixed and supposing to reach the industrial cost objectives of 1.8 ECU/Wp for PV modules, than the same plant would produce at a cost of 0.28 ECU/kWh. This demonstrates that the research action only on the PV modules is not sufficient to make the PV-kWh cost competitive with the fossil fuels-kWh.

Therefore an R & D parallel effort on B.O.S is needed. For B.O.S even more than for PV modules, a cost decrease is expected by means of a more careful system engineering and not from the research of new and cheaper conversion and transformer devices.

3.3.1 PV kWh Cost: the Grid Connected Case

For the evolution of the kWh cost of photovoltaic origin the reference case has been defined, as described in Table 12 and **Table 14**.

A grid connected plant has been considered because this is the application which will be possible to use in Europe, where the users not grid connected are a small part and where photovoltaics answers the need to improve the quality of life and therefore towards the gradual substitution of the fossil fuels generators with renewable energy grid connected plants.

For the evaluation of the kWh cost, $\mathbf{C_E}$, the expression described in Table 12 has been used

$$\mathbf{C_E = (C_M + C_B) \cdot (K_a + K_m) / (I \cdot K_T), ECU/kWh}$$

where $\mathbf{C_M}$ is the PV modules cost given in ECU/kWp and therefore in the "basic case" is equal to 3300 ECU/kWp as in Table 13.

3.3.1.1 **Photovoltaic Plants Cost**

The PV modules to be effectively used should be mounted over support structures, linked among each other in a serial-parallel configuration which makes a string; the various strings should then be linked using blocking diodes forming in this way a PV field.

The electric power rate collected at the terminals of the field should be transformed in alternate current with such characteristics that would not "interfere" with the grid standard conditions, in the case of grid connected plants.

This various actions and components which from the module takes to the practical application of the generated electric power rate is called B.O.S.

Therefore the cost of the photovoltaic plant $\mathbf{C_S}$ (ECU/kWp) is subdivided into two principal terms: cost related to the modules, $\mathbf{C_M}$, and cost related to B.O.S., $\mathbf{C_B}$.

In **Table 15** an attempt to make a comparison of the costs related to three plants different among each others for dimensions (0.66 MWp, 1 MWp, 3.3 MWp) and for country (Italy and USA) has been done. Italy was chosen because is one of the European countries more active in the sector of the large size PV plants together with Germany and Spain.

The data shown have been taken from those published and normalized among each other for an easier comparison.

The costs have been classified in an homogenous way, but there could also be some errors in their reclassification.

It can be therefore found that the plant cost varies between a minimum value of 5.4 ECU/Wp and a maximum value of 7.1 ECU/Wp and this does not depend on the plant dimensions.

The modules cost increases with the plant dimension between a minimum value of 3.6 ECU/Wp (plant of 3.3 MWp) and 4.4 ECU/Wp (plant of 0,66 MWp); but it is possible that this trend does not have anything to do with the plants dimensions but rather with the module production local situation.

On the B.O.S. cost there is even more variation because the values are between a minimum of 18% of the plant cost up to a maximum of 47%.

In this situation it is difficult to find a reference point from where to start and then to foresee an evolution trend.

This means that a deeper analysis should be carried out. Nevertheless in this paragraph an attempt to analyze the gathered data will be carried out to give at least some variation intervals.

The cost of B.O.S., $\mathbf{C_B}$, could be again subdivided into $\mathbf{C_{B,A}}$, i.e. the B.O.S. cost linked to the area and $\mathbf{C_{B,P}}$, i.e. the B.O.S. linked to the generated electric power rate.

$\mathbf{C_{B,A}}$ is referred to the costs proportional to the modules area, i.e. the occupied site area (this cost is never shown in the calculations because the site is always supposed to be a marginal one given free for PV use by the local authorities), the support structures, the cables among the various modules and among the modules strings, the junction boxes, the field fence, the hearth connections, etc.

If only the italian plants are considered, these costs alone are evaluated around 900 ECU/kWp for 110 Wp/m^2 modules, $\mathbf{C_{B,A}}$ is obviously sensitive to the modules efficiencies, which means 100 ECU/m^2.

For the evaluations given hereinafter these values will be used as a reference point for $\mathbf{C_{B,A}}$.

Being steel structures, concrete plinths, rubber and copper cables, there is not any possibility at this stage to decrease those costs in the future unless, a better more detailed engineering will be carried out to decrease the materials quantities.

Only in this way it is possible to understand the value of only 205 ECU/kWp declared for the KERMAN plant.

The other possibility is to increase significantly the modules efficiency.

With the term $\mathbf{C_{B,P}}$, as already said, the B.O.S. costs depending on the plants power rate are indicated, i.e. transformers, DC/AC converters, electric boards to subdivide the field.

Such costs are independent from the plant conversion efficiency; they could decrease in the future because of a better engineering for a better energy conversion yield.

It is certainly true that the overall efficiency of the PV plants will improve in the future because of a higher reliability of those components which at the present time suffer of some problems.

In Table 15 this term is equal to about 1400 ECU/kWp for the two italian plants and only 675 ECU/kWp for the USA one. The first value will be considered as the reference one for the plants which could be installed in Europe and the second will be considered as the value to be reached in a short time.

Finally in the B.O.S. costs enter the plants engineering automation and supervision costs, $\mathbf{C_{B,D}}$; these represent about 10% of the plants value for the italian case and only about 2% for the KERMAN plant.

Therefore the 500 ECU/kWp will be taken as the reference point whereas 100 ECU/kWp as the possible target.

Therefore, the PV plant cost in the "basic case", given in ECU/kWp, will be:

$$\mathbf{C_S \ (ECU/kWp) = C_M + C_{B,A} + C_{B,P} + C_{B,D}}$$

with the following values

$$\begin{array}{cccccccccccc} \mathbf{C_S} & = & \mathbf{3300} & + & \mathbf{900} & + & \mathbf{1400} & + & \mathbf{500} & = & \mathbf{6100\ ECU/kWp} \\ & & \mathbf{54\%} & & \mathbf{15\%} & & \mathbf{23\%} & & \mathbf{8\%} & & \end{array}$$

In the following pages the various parameters indicated in the expression shown in par. 3.3.1 in this document will be analyzed.

3.3.1.2 **Solar Radiation, I**

The cost of the PV kWh obviously depend on the quantity of solar radiation falling on the modules. In this paragraph only plant fixed systems will be discussed (technical solutions using sun tracking and concentrator systems will not be considered here) used in Europe, preferably in the Mediterranean regions, where the radiation on the horizontal plane is around an average annual value of 1650 kWh/m^2.

This value on the modules plane, which is 20 - 30° tilted from the horizontal plane depending on the latitude, becomes about 1800 kWh/m^2 per year and used as the reference point.

The radiation value could be expressed as the ratio between the kWh generated by the modules and the kWp of the installed modules and it can therefore be written

I = 1800 kWh/kWp

3.3.1.3 Actualization Coefficient, K_a

This coefficient takes into account the plant amortization rate during its life-time and it is expressed by the formula

$$\mathbf{K_a(t) = \frac{R}{1-(1+R)^{-t}}}$$

being **R** the interest installment and **t** the plants life-time expressed in years.

In the "basic case" R = 0.06 and t = 25 years.

3.3.1.4 Maintenance of the PV Plant

The given values agree on the fact that the yearly maintenance cost of the plant is less than 2% of its initial cost and this value is assumed for the "basic case".

3.3.1.5 **Transfer Coefficient, K_T**

In this coefficient all the energy losses are included between the modules and the connecting terminals in AC (grid connected plant).

	Loss Causes	Present Values ("Basic Case")	Target Volumes
E_1	Plant working threshold	3%	1%
E_2	Temperature effect	8%	8%
E_3	Electric mismatch and ohmic losses in the generator	6%	3%
E_4	DC/AC converter	5%	3%
E_5	Faults and service interruptions	5%	1%
$\sum E$	$= K_T$	25%	17%

The assumed values for each loss cause are averages from final values of different plants for life-time, size and latitude.

It is observed that at least 1/4 of the generated energy is lost for the aforesaid causes.

It is certainly worth paying attention to these losses: considering all the efforts being made to increase module efficiencies it makes little sense to see them vanishing through inefficiencies at the plant level!

Let's make a brief discussion on this losses:

E_1 - Plant working threshold

The insolation level obviously is not a constant and when the equivalent sun hour is defined the intervals of low insolation are not taken into account.

In those intervals the PV generator power rate is so low that does not exceed the working threshold of the DC/AC converters. This threshold is different for each plant and causes losses estimated in the region 2 - 4%.

It is foreseen that in the next plants this loss could be kept within 1%.

E_2 - Temperature effect

The PV modules based on crystalline silicon have an efficiency which decreases with the temperature increase.

The effect is on the Voc and it is equal to about -2 mV/°C for cells serial connected.

Because the NOCT (Nominal Operating Cell Temperature) value is of about 45°C, it means that the temperature at the cell level is 20°C higher than the ambient temperature. Therefore, with the ambient temperature of 25°C, the power rate loss is of about 10%.

Because the ambient temperature and the insolation change during the year, the power rate loss consequently changes; the value 8% is an average consolidated value in the situation of Mediterranean Europe countries. This loss factor is intrinsic to the nature of the photovoltaic generator.

E_3 - Electric mismatch losses and ohmic losses in the generator

There are losses coming from the coupling of modules, strings, sub-fields not perfectly equal as far as the electrical characteristics are concerned.

Other losses are due to the electrical mismatch between generator and load. The overall losses are evaluated around 6%.

These are loss factors which can be eliminated with a better field engineering and with better coupling systems between generator and load.

E_4 - Losses in the DC/AC

Conversion efficiencies up to 97% are published for inverters of recent installations; yield of 95% are consolidated.

E_5 - Faults and service interruptions

This is the loss factor which at present very much penalize the plants, because these are of experimental use and are used for tests only and not for a real electric energy production.

The assumed value of 5% is rather optimistic in respect to the effectively shown values, but it is pessimistic if the standard plants for electric energy production are considered. In this situation, the malfunctioning conditions should be under 1%, otherwise the praised reliability of the photovoltaics becomes unrealistic.

3.3.1.6 kWh Cost vs Plant Size

The only term sensitive to the plant size is $\mathbf{C_{B,D}}$, i.e. the cost related to the engineering, to the starting tests, to the commissioning. This cost in the "basic case" is equal to 500 ECU/kWp.

It can therefore be assumed that for very large size plants, or for several plants which use the same project, this value decreases up to become almost negligible i.e. to about 100 ECU/kWp.

In this way and keeping the same values of the "basic case" the kWh cost becomes

$$\mathbf{C_E = 0.39\ ECU/kWh \quad , \qquad C_{B,D} = 100\ ECU/kWp}$$

i.e. it decreases of 10%.

On the other hand the 100 ECU/kWp value has already been obtained for the KERMAN plant and therefore further improvements could be obtained in the future.

3.3.1.7 **PV kWh Cost vs Plant Life-Time**

The PV kWh cost strongly depends on the overall plant life-time, as it is shown in **Figure 16**.

This is obvious because the photovoltaic systems are characterized by high initial investments and low running and maintenance costs. In fact it is necessary to bear in mind that the photovoltaic electric generation method means investments rather than running costs.

For the same reason the kWh cost is strongly dependent on the way it is financed i.e. on the interest rate. The same plant whose life-time is 25 years will have a kWh cost ranging between 0.3 ECU and 0.72 ECU if the yearly interest rate ranges between 2% and 15%.

This means that the PV kWh cost is also strongly dependent on the financial policy applied to these plants and therefore on the support policy which will be adopted by the European Governments towards the photovoltaic power generation.

It is therefore necessary that the plants life-time should be of at least 25 years. In fact after this period the PV kWh cost remains virtually a constant (Figure 16).

The PV crystalline modules are certainly able to satisfy these requirements, as it is demonstrated by some of the installed plants at the beginning of the eighties which up to now have not shown any significant sign of degrade.

Whatever the production technology of future photovoltaic modules will be, their stability over time is a fundamental aspect. This consideration seriously undermines the possibility to use thin film in power plants.

This is true for PV systems without tracking and without concentration; those in fact seem to have some extra problems both at modules level (depolymerization of the encapsulant) and at tracking systems level which require extra maintenance expenses.

3.3.1.8 **Modules Efficiency Influence on the PV kWh Cost**

The PV kWh cost as a function of the modules cost in ECU/m^2 for various modules efficiencies is shown in **Figure 17**.

This graph takes also into account the effects of the conversion efficiency on the B.O.S. part dependent upon the area occupied by the modules.

It is therefore found that in the assumed hypotheses and shown as constants, the same cost of 0.44 ECU/kWh calculated for the "basic case" could be obtained, for example with modules at 10% efficiency of cells which would cost 275 ECU/m^2 or with modules at 14% efficiency of cells having a cost of 440 ECU/m^2. It can also be found that to reach the objective foreseen for 2005 of 0.25 ECU/Wp, a cell efficiency of at least 13% is necessary with a very low cost of ≈ 75 ECU/m^2.

Because it has been found that the foreseen minimum cost in 2005 for the module will be 239 ECU/m^2 (Table 13) and that the maximum efficiency considered is 15%, it means that the foreseen objective of 0.25 ECU/kWh cannot be reached working on the modules efficiency only, but it is also required to drastically reduce the B.O.S. cost.

From Figure 17 it can also be found that when the cells efficiency is too low (< 8%) the kWh cost is higher than 0.25 ECU even if the module cost was zero.

This means that for a certain B.O.S. cost the module should reach a minimum efficiency (threshold efficiency).

This aspect also penalizes the thin film modules in relation to the polycrystalline modules.

3.3.1.9 **Effect of the Transfer Coefficient K_T over the PV kWh Cost**

C_E is inversely proportional to **K_T** which can vary between the present value of 0,75 up to the foreseen value of 0.83. Higher values cannot be reached.

Consequently **C_E** could decrease from 0.44 ECU/kWh of the "basic case" to 0.40 ECU/kWh, i.e. of about 10%, all the other hypotheses remaining the same.

In a graphic form, this result is shown in **Figure 18**.

3.3.1.10 **Effect of the B.O.S Cost over C_E**

It is believed that the B.O.S. cost can be only marginally reduced with technological improvements over the three terms which make it.

In fact the $\mathbf{C_{B,A}}$ term, in principle, could be decreased only increasing the modules efficiency and the effect was seen in Figure 17; the $\mathbf{C_{B,P}}$ term could be decreased only increasing the efficiency of the converters and the effect can be seen over the improvement of $\mathbf{K_T}$ (Figure 18); the $\mathbf{C_{B,D}}$ term, finally, could be decreased only improving the plants standardization, their diffusion and the PV site management.

Nevertheless, it has been seen that the declared values for the KERMAN plant are much lower than those published for the italian SERRE and ELIO 1 plants.

The reasons for this could be several, not last the non homogeneity of the compared data; nevertheless it is thought that, at least partially, this difference is to be attributed to a greater "confidence" of the KERMAN designers with the photovoltaic technologies. This avoids to introduce on the design path a series of cautions and redundancies present in the European plants.

It can therefore be supposed that in the KERMAN plant there is a greater "maturity" which takes to lower installation costs.

Having these considerations in mind a cost evolution of the B.O.S. can be supposed as follows:

a) $\mathbf{C_{B,A}}$ **-** The "basic case" value of 900 ECU/m^2, could be decreased to 300 ECU/m^2 as an effect of a rationalization of the assembling systems and of a lightening of the supporting structures. A further decrease is expected for a module efficiency from the present 106 Wp/m^2 to 120 Wp/m^2 (η_C = 15%). These two effects produce a decrease of $\mathbf{C_E}$ of 19%.

b) **$C_{B,P}$ -** The KERMAN plant shows a cost of 675 kWp against the 1400 of the "basic case". This value is considered the target to be reached by the European plants in 2005. This implies a decrease of **C_E** of 13% in relation to the "basic case".

a) **$C_{B,D}$ -** Decreases from 500 ECU/kWp to 100 ECU/kWp as described in paragraph 3.6 with an effect of - 8%.

If the calculations are repeated with these improved B.O.S. performance the graph in **Figure 19** is obtained from which it can be observed that the target of 0.25 ECU/kWh foreseen for the photovoltaic plants in 2005 could be obtained with the present cost of the modules equal to 349 ECU/m^2 having a cell efficiency of 15% or, for example, from modules of low efficiency (but of equivalent life-time 25 years) having a cost of 180 ECU/m^2; it could be the case of the thin films modules as long as the life-time is guaranteed.

Obviously varying the B.O.S. cost all the intermediate situations can be found between Figures 18 and 19. It is therefore important to confirm if the declared B.O.S. cost in the KERMAN plant have really been reached and in which way and which results will then be effectively reached during plant operations.

It is therefore possible at this stage, to foresee a scenario in which to progressively take into account all the cost improvements obtained at module level (Figure 15) and at B.O.S. level and distributed over a time period up to 2005, it being the year in which, theoretically, it should be possible to obtain the aimed results.

It should be said that the costs evaluation was carried out identifying a "basic case" as close as possible to real situations. It represents the "minimum possible cost" compatible with the present technology.

The various inefficiencies typical of a real situation were not considered, such as, for example, high return rates due to lower process yields due to the management difficulties.

From this point of view the "basic case" represent an ideal case necessary to identify the voices of cost which can be reduced and the more effective technical actions to be carried out to improve the production process.

This is shown in **Figure 20** as a synthesis of what has been discussed above.

The indicated time schedule of the indicated events is only an hypothesis, but certainly to take the PV technology into the electric energy generation sector, a similar pattern if not the one shown should be followed; otherwise photovoltaics will remain only at a demonstrative level and will not contribute to the effective production of electric energy.

In this case photovoltaics could only give a contribution towards improvement of quality of life at primary and extra secondary needs levels and in emergency situations not otherwise possible.

3.3.2 Fossil Fuels kWh Cost

The electric energy production cost is very variable depending on countries, generation and user sites, type of plant and fossil fuels, using time, etc.

An analysis of those costs will not be carried out here, it is only stressed that the cost of the traditional electric energy is around 0,05 ECU/kWh. This value is to be attributed to the electric energy generated by the main power plants.

The real situation is very complex because the electric grid is fed by different type generators which work depending on the load demand which is different hour by hour, day by day, season by season, country by country.

As an example in **Figure 21** the load diagrams related to the italian grid respectively in a typical winter and in a typical summer working day are shown

In winter two peaks can be found, one at 10 h and another one at 17 h. In summer the peaks are less evident.

The summer situation could develop over the years when the habit to cool the working areas in the daily hours will have become more diffused as it is in USA.

Nevertheless it is believed that the graph represents a Mediterranean area where the installation of the higher number of photovoltaic plants is foreseen in Europe in the next years.

The diagram shows a correspondent base at the power rate level required for the night hours and represents the basic load.

This is fed with the main power plants working constantly, which generate at a minimum cost of about 0.05 ECU/kWh. While during the day the demand increases, more generators are switched on including those generators switched on for a short period in relation to the peaks.

The costs caused by the latter, peak power plants, are more than the double in relation to the former and are about 0.13 ECU/kWh.

To prove the above, utilities are trying by means of a fee policy, to move the domestic users from the peak hours (from 7.00 to 21.30 from monday to friday) to the empty hours (from 21.30 to 7.00 of the weekdays and saturday and sunday for the whole day). The fee ratio between empty hours and peak hours is about 1/3.

Because the PV plants work only in the daily hours, they will certainly become part of first demand peak.

It is further observed that if the PV plants are installed to sustain the grid in terminal sites, then the reference kWh cost cannot be the basic one, but the effective one belonging to a particular site, which can assume values up to 0.25 ECU/kWh.

With these considerations in mind it can be assumed that the photovoltaic electricity generation could have an effective use not only for the improvement of life at primary and extra secondary needs levels but also to easing the National Electric Grid first as a support to it in terminal sites and afterward as a demand support in the peak hours.

A production cost of 0,25 ECU/kWh can be considered as the entrance threshold for the first case; for the second case, 0.1 ECU/kWh seems to be instead a minimum possible value.

3.3.3 PV and Fossil Fuels kWh Cost Comparison

Electricity generation from PV is free of any type of acoustic or radioactive environmental pollution. It occurs without any gaseous emissions and does not therefore cause public health problems or damage to agriculture, and does not in any way affect the general and local climate.

It can be said that the main justification for the introduction of photovoltaics in Europe is the potential for reducing the gaseous emissions that are linked to the combustion of fossil fuels. Whilst it is not currently possible to establish the competitivity of PV in relation to the traditional generation in terms of the kWh cost alone, if gaseous emissions abatement is the main driving force, then the associated environmental and social benefits improve the viability of PV.

Furthermore, optimum electricity generation from photovoltaics corresponds to the period of greatest insolation which, in some regions, coincides with the period of greatest demand. During these hours the generation costs for fossil fueled plant can double compared to the average value as less efficient generating plant is called upon. The contribution from PV during peak-hours could reduce the need to upgrade the National Electric Grid to manage the peak-hour energy demand. The contribution of PV installed at the point of use should also be considered.

In addition to the "industrial" cost of the kWh from fossil fuels a "social" cost should be added to take into account all the environmental impact problems linked to the combustion. When, from the general assumptions, these costs are quantified, it is very difficult to find objective references upon which to determine accurate values.

Referring to the appropriate specialized literature, this report analyses the available data and offers some conclusions and attributes some values to the social damage linked to the effluents of the fossil fuels power plants which, excluding CO_2, increases the kWh production cost by a factor of 2. If the contribution to the greenhouse effect caused by CO_2 emissions is added, the overall social cost of generation from fossil fuels increases the initial cost by at least a factor 3.

On the negative side, the cost of photovoltaic generation is penalized by the uncertainty of the production which is dependent on meteorological factors. This uncertainty forces utilities to invest, even if only partially, in peak power plants. Therefore photovoltaic plants contribute to a reduction in the management costs but not the investments on peak power plants. To take into account such costs, it is necessary to modify the PV energy cost, C_E, with a correction factor. Assuming that analysis of the economics of a traditional fossil-fuel power plant gives an energy production cost where investment and running costs account for 1/4 and fuel costs account for 3/4 of the total. In this case the correction factor would be 0.75

Considering all these aspects, comparison of PV kWh cost with fossil fuels kWh can now be undertaken in the following way:

1) **Bulk plants**

Industrial cost	0.05	ECU/kWh
"Negative cost" for emissions	0.05	"
"Negative cost" for CO_2 (greenhouse effect)	0.05	"
Total cost	0.15	ECU/kWh

2) **Peak plants**

Industrial cost	0.13	ECU/kWh
"Negative cost" for emissions	0.10	"
Total cost	0.23	ECU/kWh

3) **Grid support plants**

Industrial cost	0.25	ECU/kWh
"Negative cost" for emissions	0.10	"
Total cost	0.35	ECU/kWh

4) **Grid connected PV plants**

Industrial cost	C_E	ECU/kWh
"Negative factor" for production uncertainty	0.75	

In agreement with the aforesaid values, Figure 20 offers an indication of the threshold values for the viable use of PV for various applications. These could have a significant meaning for the diffusion of photovoltaic electric energy.

The graph demonstrates that photovoltaic plants could be used as a support to the grid in point of use sites where the PV kWh cost is around 0.26 ECU/kWh and this, according to the hypotheses shown in Figure 20, could occur around the year 2001.

The use of PV to meet peak hour demands will be possible around 2005 where the cost will decrease below 0.18 ECU/kWh.

According to the hypothesis, bearing in mind the analysis does not attempt, for instance, to make any predictions as to possible variations in the cost of primary fossil-fuel which can be susceptible to strategic shortages as well as gluts, in the period considered it is unlikely that PV will be competitive with "Bulk generation" which requires a minimum cost of 0.12 ECU/kWh.

As was mentioned earlier, though, PV in the main generation plants is also held back because of its discontinuous character. For the use of the renewable energy sources in a quantity greater than 10% in the grid it is necessary to overcome the problem of storage which is not considered here.

The PV-kWh cost, C_E , is the result of two contributions, the module cost and the B.O.S. cost. It is desireable that both components decrease in relation to their present values by similar amounts. It is of little value to make efforts only to the decrease the module cost, C_M, if it not possible to decrease the installation and grid connection cost and vice versa. Figure 20 attempts to show that there are margins for reduction in both components.

It is vital to stress that the numerical values shown do not have clearly defined variation margins and therefore the indications should only be used in respect of their methodology rather than in terms of absolute values; the indications could perhaps be more accurately defined if a further, more in depth analysis was carried out.

3.4 EFFICIENCY, STABILITY AND COSTS FOR VARIOUS TECHNOLOGIES

As has been stressed in the introduction to this study, all the considerations in the previous chapter refer to industrial costs and do not concern price.

Before attempting to make any comparisons as to the most promising technologies some considerations on polycrystalline systems price are made.

At present, it is difficult to foresee a trend in photovoltaic system prices, but it is believed that any attempt to do so must incorporate some cost which would take into account both the trading cost and the financial cost to manufacturers.

Given the present dimensions of the production lines an increase of at least 25% is necessary to cover all of these costs and an increase of 5% to account for profit is fundamental to make the photovoltaic sector industrially viable.

According to these considerations a forecast of photovoltaic system prices is given in **Figure 22**.

The technologies comparison, found hereinafter, is again carried out considering elements of cost and not price.

The target of 0.25 ECU/kWh considered possible in 2005, at least at the demonstration plant level, is the result of a series of improvements both at module technology level and at B.O.S. level.

However, the same result could be obtained with a number of different combinations than the one hypothesized.

In **Figure 23a)** the correlation between the B.O.S. cost in ECU/kWp C_B and the module cost C_M is shown to obtain the same energy cost fixed at 0.25 ECU/kWh.

In the hypotheses indicated in the above figure, it is seen that with the present B.O.S. cost (2800 ECU/kWp), the module cost should be in the range 80 ÷ 100 ECU/m^2 for cells efficiencies around 10% and around 140 ECU/m^2 for efficiencies of about 15%.

At present there is not any technology capable to reach those costs, and in fact with the necessary efficiencies the actual kWh cost is situated around 0.44 ECU/kWh.

The cost forecast for the B.O.S. is around 1000 ECU/kWp in 2005 and therefore 0.25 ECU/kWh can be obtained with module costs between 200 and 350 ECU/m^2 when the cells efficiencies are from 8% to 15% and the plant life time is 25 years and between 140 and 260 ECU/m^2 when the plant life time is 15 years as shown in **Figure 23b)**.

In this case the cost of compatible module can reach 350 ECU/m^2 (η= 15%, t = 25 years) and it is reduced to 170 ECU/m^2 for thin films based modules (η= 10%, t = 15 years).

As far as the crystalline silicon technology is concerned, which is in a more advanced industrial phase, it is possible to analyze the costs elements with a certain precision and to indicate the technological aspects to be improved to obtain the results aimed for , as has been done in the previous chapter 2.

In the case of thin films modules, the costs evaluations at the present time and the medium term forecast are quite unreliable. However, it is possible to venture some considerations.

a) Thin films modules use a quantity of active material much lower than the one necessary with the crystalline silicon because of the reduced thickness of about a factor 100.
   This characteristic makes the costs more sensitive to the production volumes in respect to the crystalline silicon technology and therefore a significant cost reduction is expected when production lines increased from 10 MWp/year to 100 MWp/year.

b) Nevertheless the module assembly (glass, EVA, frame, box) is very similar to standard crystalline silicon modules and it is supposed that the associated costs will be very similar to those calculated for cells with a bigger area.
   From Table 13 it can be seen that the assembly cost is 80 ECU/m^2 which remains constant in the thin film case.

c) To make the thin film (CdTe, CIS, α -Si) it is necessary to use a different glass (≈ 10 ECU/m^2) covered by a transparent and conductive oxide (TCO) whose deposition, with vacuum equipment and in areas without dust (class 1000 at least), has a high associated cost. This requires high levels of investment which are more easily absorbed with the increase of production volumes.

In any case it seems improbable that the thin films modules cost will go lower than 150 ECU/m^2 when the crowning and substrates materials alone are quoted at not less than 80 - 90 ECU/m^2 .

In any case the cost of 150 ECU/m^2 is compatible with an energy cost of 0.25 ECU/kWh if the conversion efficiency is constant at 8% for a time of 15 years as shown in Figure 23b).