SIMPLIFIED LIFE-CYCLE ANALYSIS OF PV SYSTEMS IN BUILDINGS: PRESENT SITUATION AND FUTURE TRENDS

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SIMPLIFIED LIFE-CYCLE ANALYSIS OF PV SYSTEMS IN BUILDINGS: PRESENT SITUATION AND FUTURE TRENDS

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Abstract

The integration of photovoltaic (PV) systems in buildings shows several advantages comparing to conventional PV power plants. Main objectives of the present study are the quantitative evaluation of the benefits of building-integrated PV systems over their entire life-cycle and the identification of best solutions to maximize their energy efficiency and CO_2 mitigation potential. In order to achieve these objectives, a simplified Life-Cycle Analysis (LCA) has been carried out. The methodology has been applied to PV systems in two steps: Firstly, a number of existing applications have been studied. Secondly, a parametric analysis of possible improvements in the Balance-of-System (BOS) has been developed and included in the model. Finally, the two steps have been combined with the analysis of crystalline silicon technologies. Results are reported in terms of several indicators: energy pay-back time, net avoided CO2 emissions, CO2 yield, and specific CO2 emissions. The indicators show that the integration of PV systems in buildings clearly increases the environmental benefits of present PV technology. These benefits will further increase with future PV technologies.

1. Introduction

During their use, PV systems cause no emissions. Nevertheless, as any other industrial product, in order to be manufactured, installed (upstream processes) and decommissioned (downstream processes), PV systems need both materials and energy flows, which affect the environment. Today, this environmental impact is considered as negligible, but it has to be taken into account for a correct assessment of different energy options in future scenarios forecasting a large-scale use of PV.

The integration of PV systems in buildings shows several advantages with respect to conventional PV power plants in open fields. Major benefits are the occupation of ground and surfaces that are already used for other purposes, the saving of construction material needed for PV module supporting structures, the substitution of building envelope materials, and the possibility of recovering a significant fraction of the thermal energy dissipated by the PV panels.The present work analyzes the entire life-cycle of some selected PV systems, in order to identify best opportunities for reducing CO_2 emissions and increasing their overall energy efficiency. Given the interesting features

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of these systems, the study dedicates particular attention to applications in buildings. The objective is twofold: the first goal is to quantify the relevance of BOS in terms of energy consumption and emissions during manufacturing and installation of PV systems. The second objective is to quantify the benefits of the integration of PV systems in buildings over their entire life-cycle, in terms of energy consumption and related emissions (during upstream processes), energy production and related *avoided* emissions, materials (raw and auxiliary) consumption and releases to the environment. Both the use of building structures to support PV modules and the substitution of building envelope materials are analyzed in detail in order to identify best solutions. Both present and future crystalline silicon technologies are considered in the analysis.

The methodology of Life-Cycle Analysis (LCA) has been applied to PV systems in two steps: firstly, a number of existing applications have been studied, namely the Serre power plant and several examples of integration in buildings. Secondly, a parametric analysis of possible improvements in the Balance-of-System (BOS) has been developed and included in the model. Finally, the two steps of the analysis have been combined with the analysis of crystalline silicon technologies. Results are reported in terms of several indicators: energy-pay-back-time, net avoided CO_2 emissions (CO_2 balance during lifetime), CO_2 yield, specific CO_2 emissions, and CO_2 -pay-back-time.

1.1 **Methodology: the Simplified Life Cycle Analysis**

Life-Cycle Analysis (LCA) is a methodology aiming at evaluating the environmental burden of a product, a process or a service throughout its whole life-cycle, from the extraction and processing of raw materials, to its final dismantling, recycling or disposal. In principle, the "full" methodology is able to provide a complete evaluation of environmental disturbance, i.e. it is able to synthesize the contribution of all pollutants or potential environmental pressure drivers into the so-called "environmental profile" of the system under analysis.

However, given the complexity of the systems studied and the wide range of materials involved in the analysis, a *simplified* LCA has been carried out. As a result, the environmental profiles of the different systems are only reported in terms of energy and CO_2 emissions.

The following assumptions and simplifications have been adopted:

- In the case of PV, data on both manufacturing and energy production varys from place to place. Italian average data have been adopted for all the parameters that are site-dependent, such as: average annual insolation (the adopted value is 1700 kWh/m^2 on a 30° tilted surface), energy consumption and CO_2 emissions related to PV module manufacturing, efficiency and CO_2 emissions of the electricity production mix. The latter figures have been calculated by adapting a specific software (TEMIS) to the Italian boundary conditions [AMBIT 1995]. All the above assumptions may be considered as reasonable approximations.
- As far as the production of BOS materials is concerned, energy consumption and CO_2 emission values can vary extremely from Country to Country and even from a manufacturing plant to another. Several data-bases have been reviewed. Average values have been used for calculations.
- All PV systems considered in the analysis are connected to the electric grid
- System boundaries have been defined as follows:
  - * The combination of PV module manufacturing, materials for BOS and PV energy production (both electric and thermal) has been considered as the "system" to be analyzed;
  - * Mining of raw materials is not included in the analysis;
  - * All transportation steps are excluded;
  - * Due to the lack of reliable data, recycling has not been taken into account;

- With respect to the time framework, results are presented both for present (1995) PV crystalline silicon technology (“base” scenario) and for future technologies. Two possible amelioration levels (“advanced” and “optimized” scenarios) have been taken into account. The optimizations considered here are certainly technically feasible and do not rely on any significant technological break-through. The actual time of adoption for large-scale production by industry will then depend on the evolution of R&D programs, investments and PV market.

2. Analysis of the Balance Of System (BOS)

2.1 Types of Installations

For the comparison of PV systems two major categories are identified, namely “conventional” installations (here named PV fields), and PV systems in buildings. The latter can be further classified into sub-categories, corresponding to the part of the building on which the PV system is applied (terrace or flat rooftop, tilted roof, facade etc.). Furthermore, the classification depends on whether the PV system is mounted on existing structures (retro-fit systems) or designed together with a new building (integrated installations). The different types of installations considered in the analysis are synthesized in Tab. 1:

PV field	Conventional PV plant in outdoors fields; this installation requires a careful preparation of land, and special structures to support the PV panels. Exposure of panels to the solar radiation is optimized by means of fixed south-oriented structuresor tracking systems. An electric efficiency of 85% has been assumed for these systems.
Terrace	In this type of installation, PV modules are fixed on the flat surface of the rooftop by means of suitable light structures. Exposure is optimized (fixed panels, south-oriented).
Tilted roof (retro-fit)	PV modules are directly applied on the existing surface of the roof. The sun exposure cannot be always optimal, since it is a “retro-fit” operation. Electric system losses can be higher. A mean “BOS efficiency” of 90% of he optimal reference case (PV field or terrace) has been therefore considered.
Tilted roof (integrated)	The PV system and the building are designed together. The possibility of planning a better exposure of the panels and of using cell cooling systems leads to a slightly higher “BOS efficiency” , which is estimated to be 95% of the reference case. PV panels substitute parts of the roof from the beginning of the project. Thus there is an additional energy saving due to the construction materials which are not used in the roof part covered by the PV panels.
Facade (retro-fit)	PV modules are used as cladding materials for covering an existing facade. The BOS efficiency is only 62% of the optimal case because of the reduced incident radiation on a vertical surface at the latitude of Central Italy.
Facade (retro-fit)	PV system and the building are planned and designed together. The BOS efficiency is 2% better than the retro-fit facade. As usual, there is also an energy saving due to the substitution of the conventional construction materials with PV modules.
Systems with heat recovery	BOS efficiency is the same as for integrated systems. Additionally, a mean heat recovery of 2 kWh_{th} per kWh_{el} produced has been taken into account.

Tab. 1 - Classification of different PV installation types

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[1] Silicon cells efficiency decreases when temperature increases.

2.2 Existing installations

Specific primary energy contents and emission factors of various materials used for calculations are shown in Tab. 2. Of course, large differences may occur depending on the type of material, manufacturing process, and on the production site. The table indicates *average* values taken and adapted from various sources. Fig. 1 shows the primary energy content of the BOS of present PV systems. Several Italian plants have been analyzed in detail, namely the ENEL power plant in Serre (3.3 MW_p), the retrofit system at the German School of Rome (20 kW_p), and a retrofit facade in an building property of ENEL in Rome (1.3 kW_p). Furthermore, the PV tile as produced by the German company BMC has been studied. Other retrofit and building-integrated systems described in literature are also reported for a systematic comparison [LES/ETH/PSI 1994, Hynes et al. 1995].

	Material energy content		**CO_2 specific emissions**
	total primary energy	**of which electricity**	**total**
Materials	**MJth/Kg**	**kWhel/kg**	**kg CO_2/kg**
steel	32.00	2.20	1.91
primary aluminium	198.00	17.00	10.59
secundary aluminium	12.60	0.00	0.51
light concrete	4.40	0.10	0.28
concrete	1.63	0.04	0.16
armored concrete	6.06	0.15	0.40
copper	70.00	4.72	3.09
glass	14.40	0.12	0.77
PVC	66.80	4.26	4.20
clay	10.70	0.05	0.66

Tab. 2 - Energy primary content and CO_2 specific emissions of BOS materials. Average values adapted from [Alsema 1994, APME 1994, BEW 1994, DBRI 1994, ENEL 1991, IVAM 1993, Hynes et al 1995, Sage 1993, Sidoroff 1994]

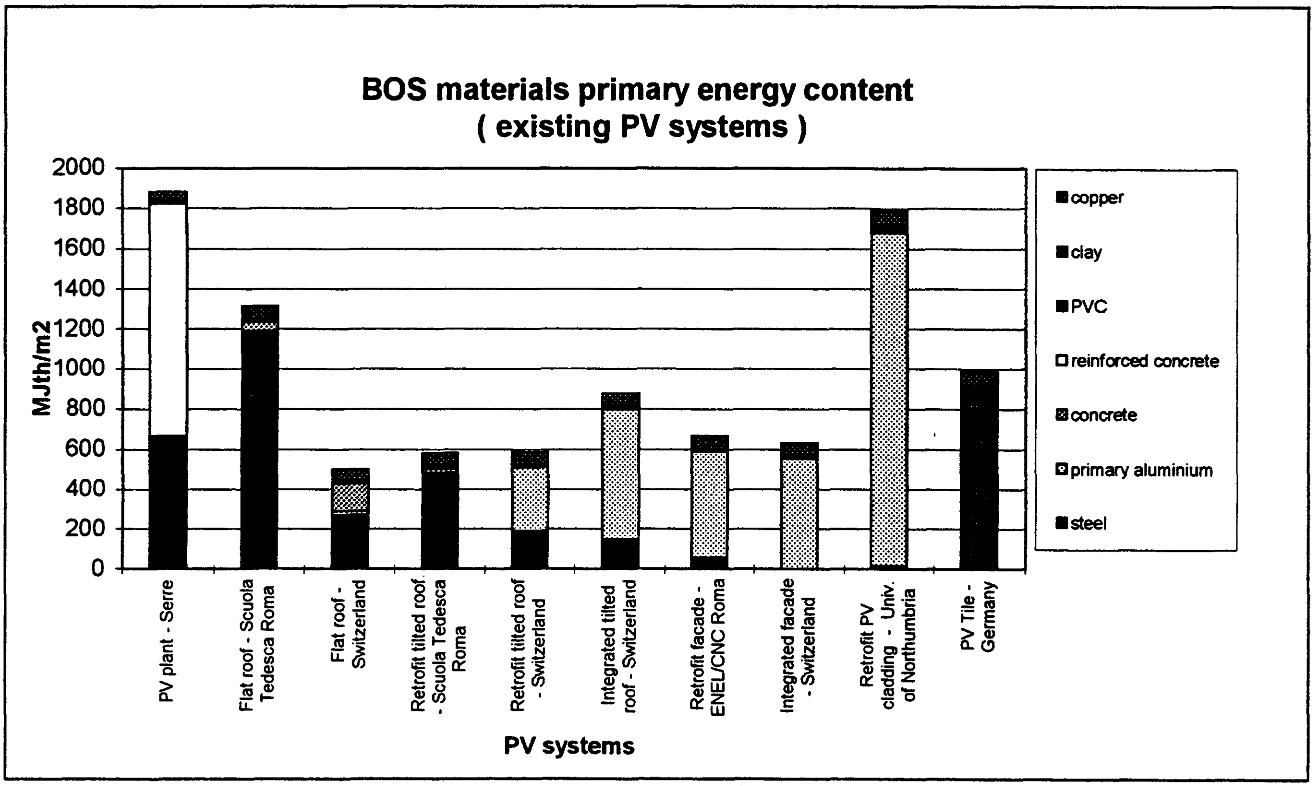

Fig. 1 - Primary energy content of the BOS of present PV systems

The first remark to be highlighted is the high primary energy content of the BOS in the Serre power plant (slightly more than 1800 MJ_{th}/m^2). This value is much higher than the corresponding figure for the majority of PV systems in buildings. This is mainly due to the large quantities of reinforced concrete and steel needed for the structures supporting PV modules. Thhese structures will always be necessary in open-field PV power plants. It should also be observed that data on BOS energy consumption have rather prudent in the case of Serre, since the plant represents the real state-of-the art of such type of systems. As a matter of fact, the BOS material requirements of this plant are much lower than those of similar European installations, e.g. Phalk 500 in Switzerland [LES/ETH/PSI 1994][2].

In contrast, most of the systems in buildings show a total primary energy content of around 600 MJ_{th}/m^2. Main exceptions are the flat roof at the German School in Rome and the PV cladding system at the University of Northumbria. In the first case, this is due to an excessive use of steel for the supporting structures. In the second case, 93% of the total BOS primary energy content is caused by the large use of very energy-intensive primary aluminium [Hynes et al. 1995]. Although to a less extent, primary aluminium is also responsible for the BOS energy content of integrated tilted roofs [LES/ETH/PSI 1994]. Finally, the PV tile shows a relatively high energy content, which is attributable to the large quantity of clay needed (almost 1,7 m^2 per m^2 of PV modules).

2.3 Future installations

In the future, PV installations in buildings will likely be designed taking into account the full life-cycle of materials. This is necessary for an energy-conscious, energy efficient and environmentally sound design of the systems. In order to maximize energy efficiency and minimize environmental impacts, two approaches can be followed, namely minimizing absolute quantities of materials and using a large fraction of recycled, secondary materials.

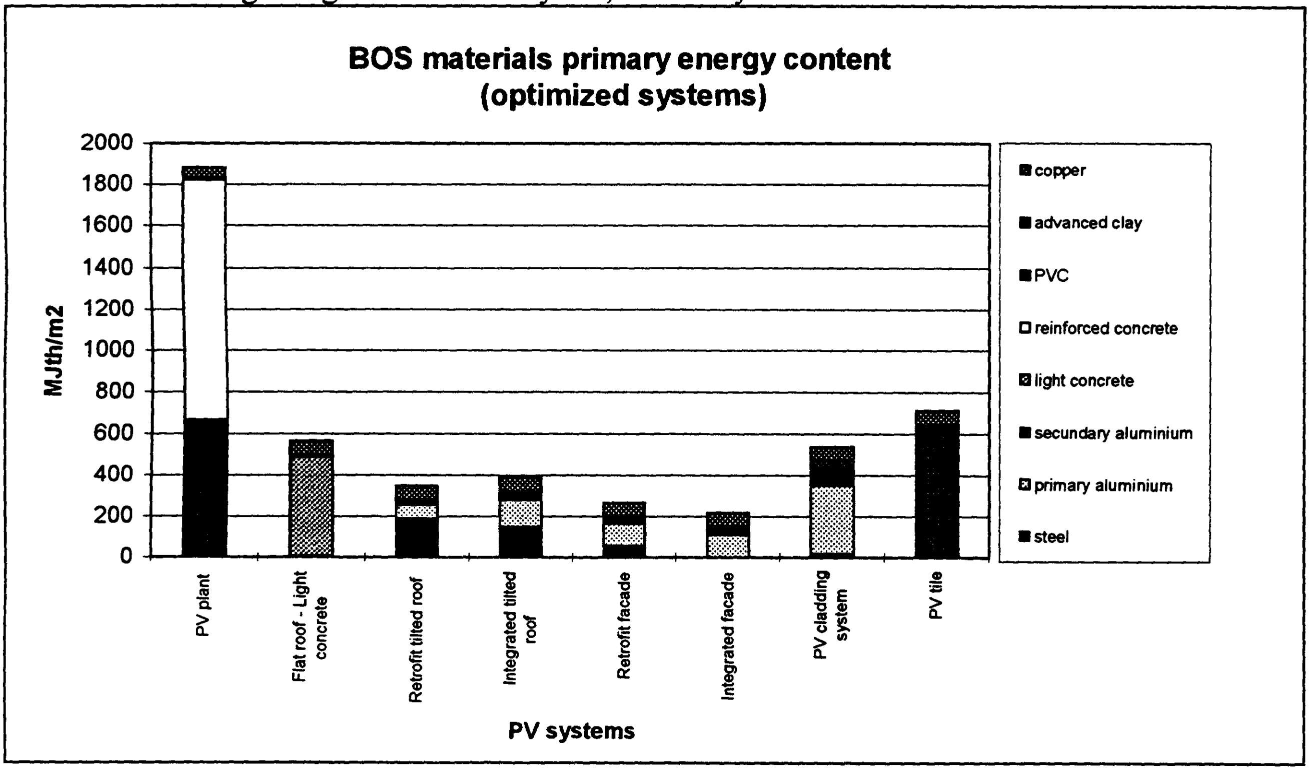

Fig. 2 - Possible future primary energy content of optimized PV systems

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[2] For this reason, the figures for Serre have been used also for the future installations.

Fig. 2 shows the possible future primary energy content of optimized PV systems according to the scenario depicted, which is characterized by the following assumptions:

- in all cases where aluminium is used, it is assumed that future installations will contain 80% of secondary aluminium. This strongly decreases energy consumption for most PV systems in buildings;
- in future, light concrete supporting structures will likely be used for PV systems on flat roofs, both for economic reasons and due to easy mounting and maintenance;
- in future, an advanced clay will be employed for PV tiles, which allows an energy consumption reduction by around 30%.

If all the above mentioned factors are taken into account, the comparison between the BOS energy content of PV plants and PV systems in buildings becomes radically favorable to the latter. This situation is clearly illustrated in Fig. 2.

3. Energy and environmental profiles of crystalline silicon PV systems

3.1 Energy

3.1.1. Present Situation

Fig. 3 shows the Energy Pay-back time (EPBT) of different PV systems based on present monocrystalline silicon modules (1995 production status). The EPBT is the time needed for the PV system to supply the amount of energy consumed for its production. It is defined as:

EPBT (years) = Consumed energy for system production / Annual energy produced by the system

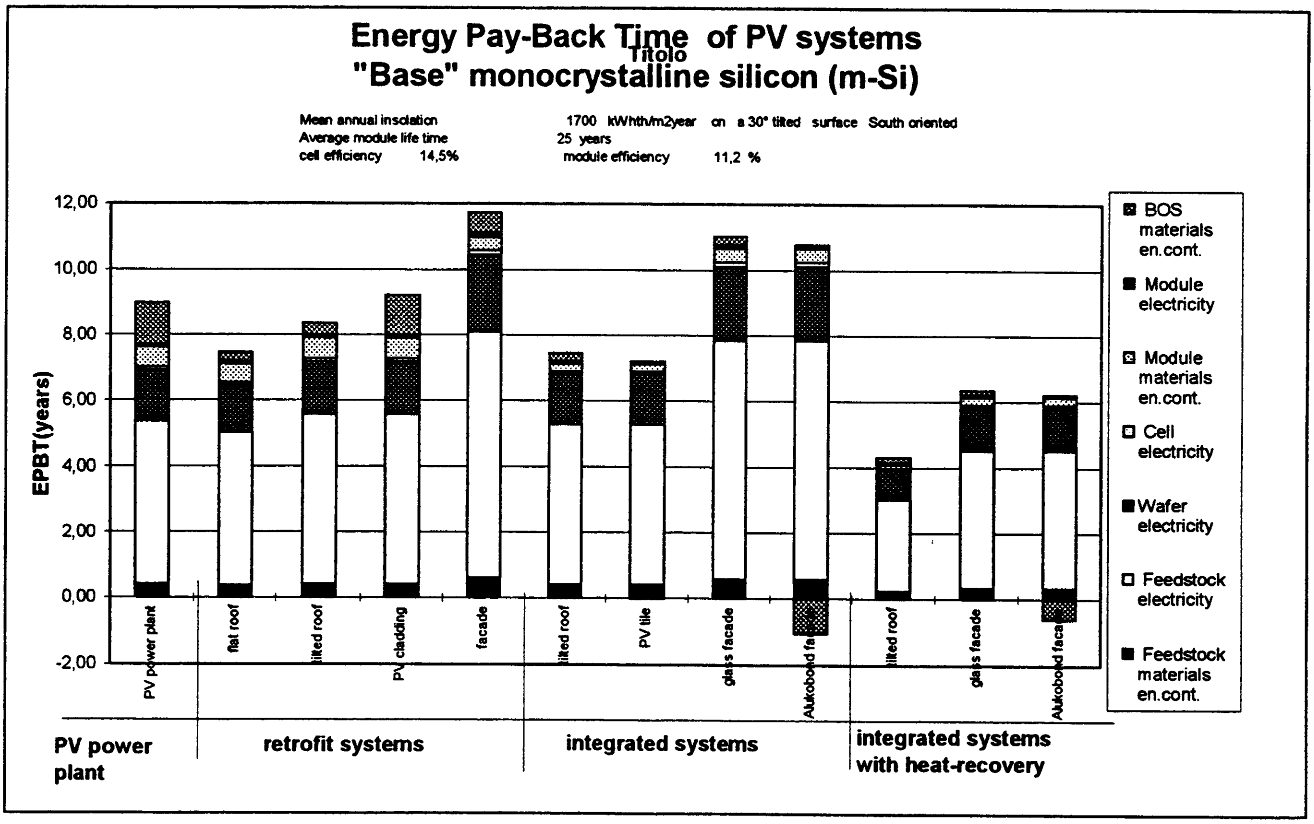

Fig. 3 - Energy Pay-back time (EPBT) of present monocrystalline silicon PV systems

The EPBT of present PV systems is quite high, even if they are installed in places with a relatively high sun radiation, such as Central Italy. With these boundary conditions, the EPBT of a PV field is 9 years[3]. The main reason for this high EPBT is the low-efficient crystalline silicon cell production process. Indeed, present crystalline silicon production processes are not optimized for PV cell and energy production. They are very low-efficient in terms of use of both material resources and energy. For instance, in 1995, 29 g of electronic-grade silicon and 162 g of metallurgical-grade silicon were needed for the manufacturing of a single monocrystalline silicon wafer of 8 g [Frankl 1996]. Combining these data with the high specific energy consumption of silicon purification and handling processes of the electronic industry leads to very large energy consumption rates. As an example, it was estimated that the monocrystalline silicon module production presently (1995) requires around 9700 kWh_{el} /kW_p of electricity and almost 3700 kWh_{th} /kW_p of process heat and primary energy content of materials [Frankl 1996]. The consumption rates for polycrystalline silicon are even worse due to a lower silicon mass yield. As a consequence, at present both monocrystalline and polycrystalline silicon PV technologies show very high EPBTs[4].

Due to the large contribution of PV modules, the installation of PV systems in buildings reduces the EPBT only to a limited extent (max. by 18% for PV tiles). Facades show even worse results because of the bad exposure to the sun at these latitudes. The most effective PV system seems to be the simple installation on flat roofs. However, the EPBT is strongly reduced if the possibility of heat recovering is taken into account. As a matter of fact, the full integration of PV systems in buildings allows for the recovery of thermal energy, which is not feasible with simple retrofit installations on rooftops. At least part of the heat dissipated by the PV panels can be recovered by means of an air channel between the back-plates of the modules and the roof (or facade) itself. This air flow has a double effect: first, the warm air can be used in the building for air conditioning and/or pre-heating of water; second, it cools down the cells, thus increasing their efficiency. A detailed analysis of the thermal energy recovery for the different installations would require the exact knowledge of too many parameters, and it exceeds by far the goal of present analysis.

In this study, an annual mean value of 2 kWh_{th} recovered heat per kWh_{el} produced by the PV system is assumed. This value was taken according to some installations in Switzerland [Posnansky&Gnos 1994]. These installations are particularly simple, since they use only small air fans as auxiliary systems to provide air circulation. Computer simulations show that on average the quantity of heat output from hybrid PV/Th components might be much higher [AMBIENTE ITALIA 1996]. Nevertheless, the rather prudent value of 2 kWh_{th} / kWh_{el} was assumed here in order to take into account eventual heat losses and difficulties to effectively recover and use the thermal energy throughout the whole year. To calculate the corresponding primary energy, the substituted heat has been supposed to be produced by methane boilers.

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[3] Other parameters used for calculations are:

- PV plant electric BOS efficiency: 85%
- efficiency of Italian electricity production mix: 39,1%; grid distribution losses: 7%
- for integrated systems, the primary energy content of the building materials substituted by the PV components have been subtracted from the BOS primary energy content shown in Figg. 1 & 2.

[4] It should be noted, that the main contribution of the energy content of present PV modules is due to the preparation of the silicon *feedstock*. This value is so high only if the energy consumption is *fully allocated* to the PV industry. This approach might be discussed, since today most of the crystalline silicon is produced from waste of the electronic industry. As a consequence, according to the LCA mass allocation approach, the PV industry should account only for 10% of energy consumption and related emissions. However, we think that PV industry should account for 100% of its consumption for three reasons, namely: i) in a near future, the demand for electronic-grade silicon scraps by PV industry will exceed the offer by the electronic industry; ii) already in the past, the products (not the waste) of some electronic industry of Eastern Europe has been totally used for PV cell production; iii) this allocation procedure allows an easier comparison between present and future PV technologies.

As shown in Fig. 3, the thermal energy recovery in present applications (tilted roof) can reduce the EPBT by more than a factor 2 with respect to a PV power field. It is also worth noticing that the PV facades become interesting when equipped with a heat recovery system.

3.1.2. Future Trends

In future, the manufacturing of crystalline silicon cells will require significantly less energy. Whatever the exact technology (monocrystalline and polycrystalline silicon derived from electronic industry, or solar-grade silicon), the production chain will be optimized for solar energy cell manufacturing. A smaller amount of silicon feedstock will be required to produce a cell. The cell and module efficiencies will also increase. For instance, it has been estimated that in a near future "advanced" monocrystalline silicon cells will have 16% efficiency and will require slightly less than 6000 kWh_{el} electricity per installed kW_p and 2700 kWh_{th} / kW_p other primary energy. On a longer term, the efficiency will further increase up to 18% and the consumption rates will decrease down to only 1900 kWh_{el} / kW_p of electricity and 700 kWh_{th} / kW_p of other primary energy [Frankl 1996].

As a consequence, the expected EPBT of such "optimized" monocrystalline silicon (m-Si2) power plant is reduced by more than a factor three with respect to present power plants (from 9 years down to 2.8 years) (see Fig. 4).

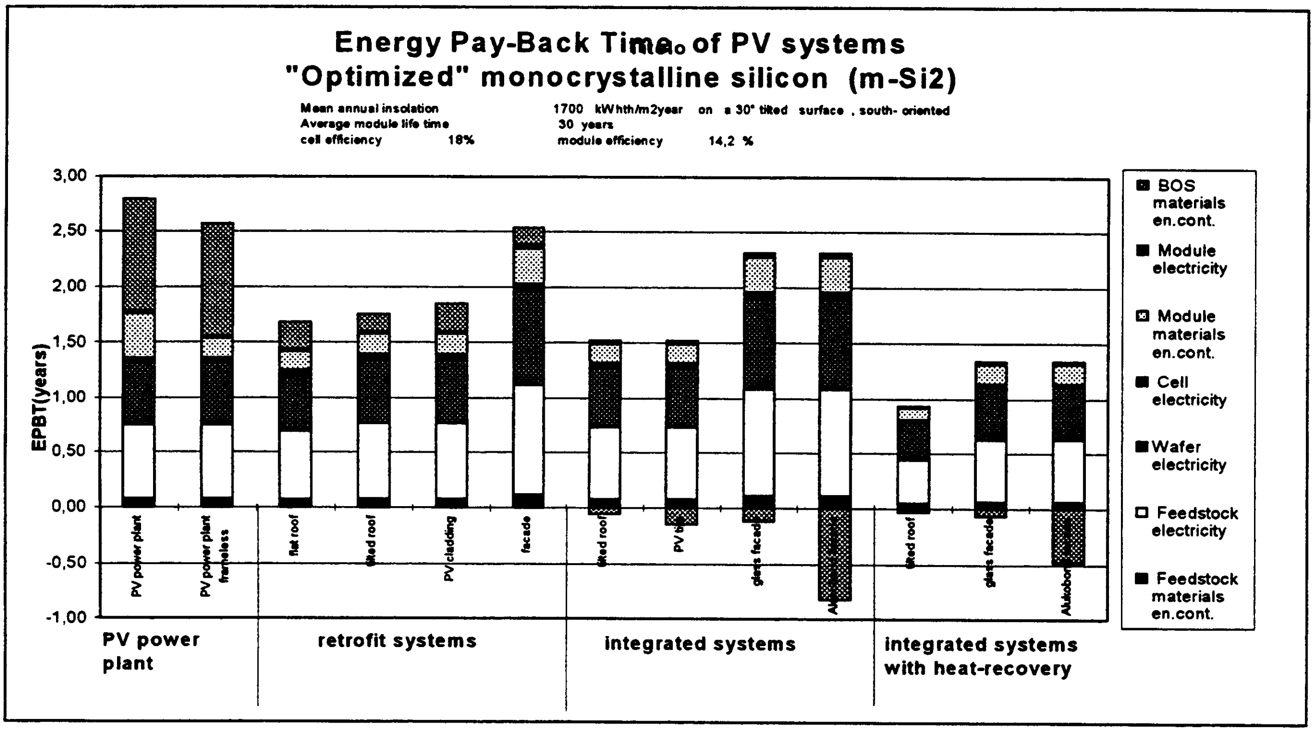

Fig. 4 - Expected Energy Pay-Back Times for future monocrystalline silicon PV systems

Moreover, thanks to the reduced energy consumption for module manufacturing, the BOS plays a more important role in the global energy balance. This means that the integration in buildings gives proportionally more benefits than today. The EPBT of a fully roof-integrated m-Si2 PV system is expected to be about 45% smaller than that of a PV field - see Fig. 4. The expected EPBT of an integrated tilted roof with heat recovery is as low as 1 year.

By that time, another important benefit will derive from the use of frameless modules. Fig. 4 shows this effect in the case of power plants. In all other PV installations in buildings the modules are assumed to have no aluminium frame.

Finally, the negative BOS contribution for PV integrated facades and roofs should be remarked. This (theoretical) result reflects the possible use of PV modules to replace conventional building cladding materials. The result is particularly significant in the case of Alukobond panels[5]. The energy needed to manufacture a 1 mm thick aluminium foil is very high, and this value is higher than the energy consumption related to the BOS of PV facade-integrated systems. As a consequence, the BOS contribution is negative. The planning and design of a PV facade instead of an Alukobond facade can be therefore considered as a conceptual energy saving measure. Although purely theoretical, this result highlights the need for energy-conscious architects and engineers to be aware of the hidden energy contents of building materials.

3.2. Environmental Benefits

One of the most important goals of the LCA is to quantify the environmental benefits of PV systems *vs.* conventional energy sources. These benefits can be evaluated, for instance, in terms of avoided emissions of CO_2. The indirect air emissions have been calculated according to the Italian electricity production and distribution mix. An emission factor of 0.531 kg CO_2 / kWh_{el} (production) has been used for the manufacturing of BOS materials and to estimate the emissions avoided by conventional PV power plants. This factor takes into account the distribution losses of the electricity produced by PV fields. In contrast, building-integrated systems do not have such losses, since the electricity is supposed to be consumed in the same place or area where it is produced. Therefore, the emission factor of the distribution mix - 0.567 kg CO_2 / kWh_{el} - has been used in this case [AMBIT 1995]. As far as thermal energy production is concerned, a specific emission factor of 0.198 kg CO_2 / kWh_{th} for natural gas boilers has been taken into account. Of course, the avoided emissions would be higher if the substituted heat were produced by oil or coal burners. Fig. 5 shows the CO_2 balance of present PV technology (1 kW_p monocrystalline silicon PV modules).

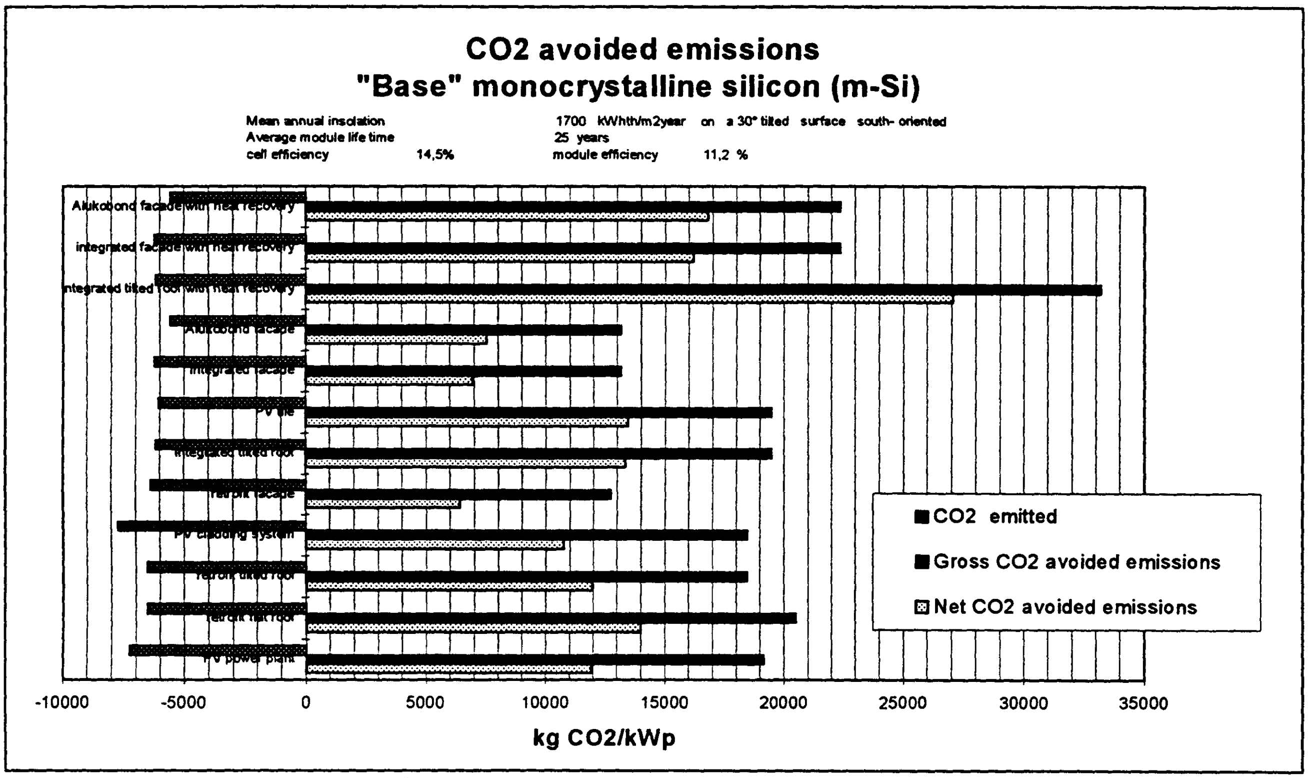

Fig. 5 - CO_2 balance of present monocrystalline silicon PV systems

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[5] An Alukobond panel is made by a sandwich of two thin aluminium foils (total thickness from 1 to 3.5 mm) with a hard rubber layer in between. These panels are often used in modern office buildings

As expected, the CO_2 emissions produced during the manufacturing and installation of all system types taken into account are significant, especially if they are compared with the emissions avoided by the systems during their estimated life-time (25 years). The net avoided emissions of PV roofs are higher than those of PV power plants. In contrast, the net avoided emissions of the PV cladding system of the University of Northumbria are lower because of the high quantity of indirect CO_2 emitted during the production of the aluminium structures. Facades also have significantly lower figures, due to their bad insolation conditions at Italian latitudes. However, the avoided emissions are higher if heat is recovered. As a matter of fact, Fig. 5 shows that the net avoided emissions by integrated roofs with heat recovery can be 2.25 times higher than the ones avoided by PV power plants. This can be also indicated in terms of CO_2 yield, defined as:

CO_2 yield = gross CO_2 emissions avoided during lifetime of PV system / CO_2 emitted during production of PV system

Today, conventional PV power plants have a CO_2 yield of 2.6, while PV roofs with recovery of thermal energy have a value of 5.4. It is worth recalling that results concerning hybrid systems should be interpreted with some care, since they still require more detailed investigations and further experimentation. However, this is a clear indication for the high environmental potential of this particular kind of systems. More detailed LCAs of hybrid systems are needed in the future, in order to take into account the downstream use of the recovered heat. When the attention is focused on CO_2 Pay-back-times, results are similar to those of EPBTs.

The environmental benefits of PV systems in buildings will significantly increase in future, as energy consumption and emissions during manufacturing of modules will strongly decrease, whereas efficiencies and lifetimes are expected to increase.

Fig. 6 shows expected CO_2 - yield values for future PV systems, basing on both monocrystalline and polycrystalline silicon technologies[6] [Frankl 1996]. he figure shows that PV systems have a relevant potential for improving their environmental performances. CO_2 yield values range from present worst case of polycrystalline silicon power plants (around 2) to the best future cases of optimized polycrystalline[7] integrated silicon roofs (20 for simple roof and 34 for roofs with heat recovery). If the amount of CO_2 emissions avoided through the substitution of Alukobond panels are also taken into account, the expected CO_2-yield value increases up to 38 (this is a rather theoretic result, however).

The figure indicates that the environmental benefits of integrating PV systems in buildings with respect to conventional power plants will increase in the future. For example, the CO_2 yield for an integrated PV roof with heat recovery is expected to be around three times higher than that of a conventional power plant.

The significant improvement achievable by PV systems can also be expressed in terms of specific emissions during lifetime. Today, a monocrystalline silicon PV power plant has a specific emission value of around 0.2 kg CO_2 / kWh_{el}. This is mainly due to indirect emissions deriving from

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[6] Following technological parameters have been used for the analysis [Frankl 1996]:

	m-Si	p-Si	m-Si1	p-Si1	m-Si2	p-Si2
cell efficiency	14,5%	12,5%	16%	14%	18%	16%
module efficiency	11,2%	10,3%	12,9%	11,5%	14,2%	14,5%
CO2 emissions during module manufacturing (kg CO2/kWp)	6288	8366	3861	3896	1354	994
module lifetime (years)	25	25	25	25	30	30

[7] Interestingly, polycrystalline silicon is expected to have best environemental profiles in the future. Despite of lower cell efficiencies as compared to monocristalline silicon m-Si2, p-Si2 is expected to have comparable module efficiencies (square p-Si2 cells use much better the space available in modules than m-Si2 cells derived from circular Czochralsky ingots) and much less electricity consumptions and total emissions during manufacturing of modules.

high electricity consumption during manufacturing of modules. In future, this value is expected to drop as low as 0.06 kg CO_2 /kWh$_{el}$ for PV power plants and 0.04 kg CO_2 /kWh$_{el}$ for integrated PV roofs [Frankl 1996].

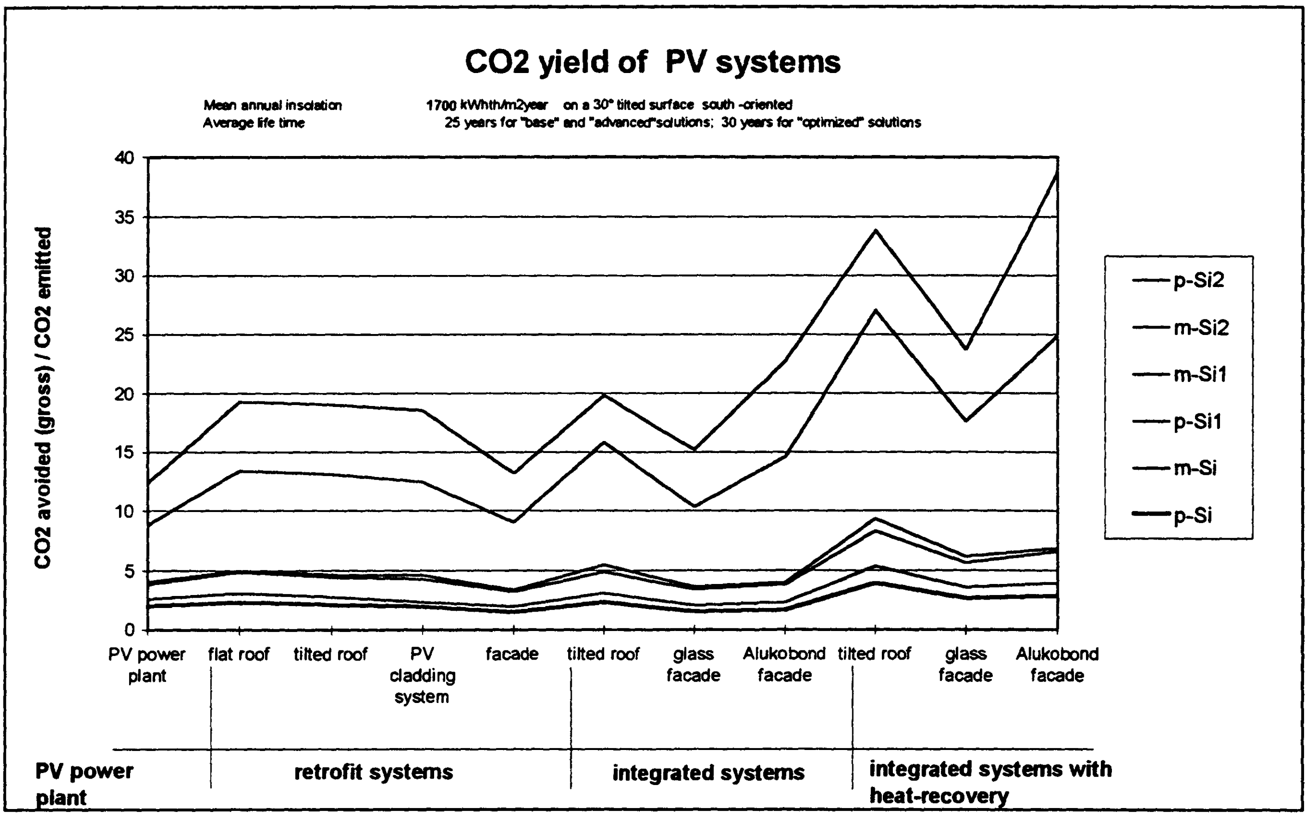

Fig. 6 - CO_2 - yield of present and future crystalline silicon PV systems

4. Conclusions

The study clearly demonstrates that a parametric LCA is one of the most appropriate tools for assessing both energy and environmental performances of PV systems. Not only it provides an evaluation of existing technologies, but it also allows the identification of future optimal solutions that should be adopted to support a large scale diffusion of PV systems. Indeed, the authors believe that LCA may offer helpful and powerful guidelines for a more efficient design manufacturing and application of this renewable energy technology. Several results obtained support this belief.

Already today the integration of PV systems in buildings presents favorable effects when compared to conventional PV power plants, both in terms of energy production and CO_2 avoided emissions. These benefits substantially increase if the installation allows the recovery of part of the heat dissipated by PV panels. For instance, today, conventional PV power plants have a CO_2 yield of 2.6, while PV roofs with recovery of thermal energy have a value of 5.4.

The analysis forecasts that these benefits will further increase for future PV technologies, as the latter will be certainly characterized by lower energy consumption during module manufacturing. For example, a CO_2 - yield of 20 is expected in future for integrated PV roofs and a value of 34 for integrated roofs with heat recovery.

Finally, the study suggests that "energy-conscious" architects should take into account energy content of materials, in order to maximize the environmental benefits of PV systems over their whole life-cycle.

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