Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp76-82)

Sustainable Energy and Economic Evaluation in Stand-Alone Photovoltaic Systems

SONIA LEVA
Dipartimento di Elettrotecnica
Politecnico di Milano
Piazza Leonardo da Vinci, 32
MILANO – ITALY

DARIO ZANINELLI
Dipartimento di Elettrotecnica
Politecnico di Milano
Piazza Leonardo da Vinci, 32
MILANO – ITALY

Abstract: - The paper introduces hybrid photovoltaic/diesel generation systems for supplying remote power plant taking into account the enhancement of the sustainable energy on the economic point of view. In particular, a cost evaluation is performed on a real plant showing the effect and weight of the sustainability on the economical saving.

Key-Words: - Renewable source of energy, photovoltaic systems, sustainable energy.

1 Introduction

The continuous decreasing of the costs of technologies associated to renewable energy sources together with a consolidated know-how of the relevant industry, bring to an increasing application of these renewable generation units in isolated electric plants.

In particular, the combination of renewable electric generation systems – that include batteries for energy storage – with diesel generators can reduce the battery size and increase the reliability of the supply.

These systems so-called “hybrid” permit to decrease the fuel consumption of the diesel-machine in the range of 70÷90% as regards to only battery-diesel supply architecture. Therefore, the primary source of electric energy for the plant becomes the renewable one, while the diesel machine constitutes the auxiliary source in case of emergency, loss of the main supply or for battery charge.

The hybrid systems can be very effective in terms of sustainable energy development, permitting a generation of electric energy with a minor environmental interference.

After a discussion on the update topic of sustainable energy programs, the paper presents an economical evaluation of photovoltaic (PV) application for stand-alone plants where sustainability assumes an important role. In fact, political decisions and people sensibility are going towards the recognition of the economical burden associated to “environmental” and “social” costs that can ransom renewable energy also from the economic point of view. Nowadays, some countries consider the social costs using the carbon tax.

The paper introduces hybrid photovoltaic/diesel generation systems for supplying remote power plant - a mountain hut - taking into account the enhancement of the sustainable energy on the economic point of view. In particular, a cost investment evaluation is performed on a real plant showing the effect and the weight of the sustainability economical saving.

2 Sustainable energy for the development

The world energy scenario is deeply changed in these last years and the attention has been moved on the environmental effects of the energy cycle trying to establish a connection between energy, development and sustainability.

The sustainability concept has its roots in a correct use of sources and-among they particularly important is the energy, that is part of all human activities. The availability of energy, the cost and the impact of energy choices on the environment, are factors that influence the community development.

Sustainability and environmental balance are real problems. The proposed solutions, as a large spread of alternative energy sources to ingrate the classical ones, represent the deep consciousness of the need of cultural changes with the support of the technology, essential tool making possible new strategic solution for energy production.

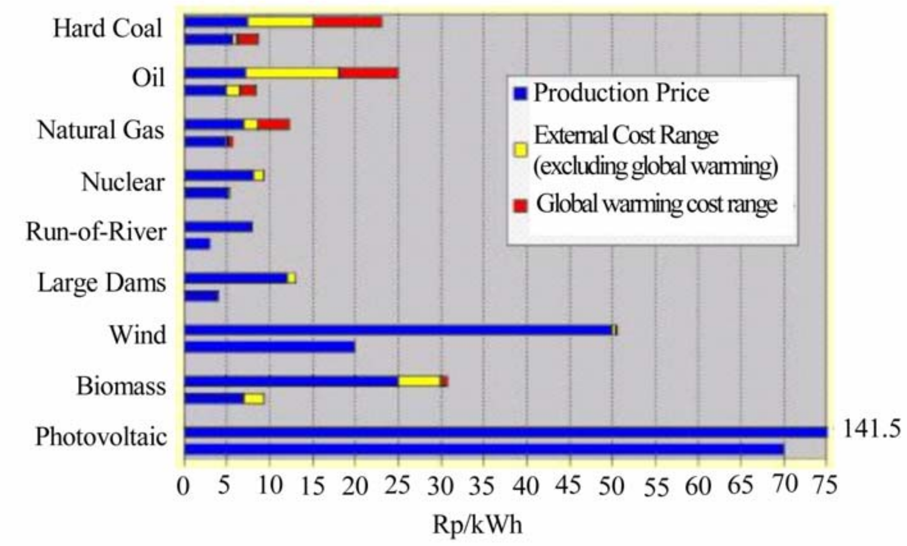


Fig.1. Internal and external (environmental) costs of electricity production. For each energy carrier two cases are shown - one representing the lower range of values and the other representing the upper range.

Nowadays, for determining the cost of energy source the main factors are its availability and the charges for its introduction on the market. The costs for the environmental impact due to the energy use are missing at the present. This fact permits that the energy sources from gas or oil or fossil result today economically convenient and widely used [1].

Renewable energy sources, and in particular solar technology, are considered in the actions to promote a sustainable development both for the environmental advantages that they offer, and for the trend of their costs that continue to decrease.

In spite of this, from the point of view of the possible spread of the photovoltaic in the energetic market, the cost of the systems and consequently of the energy that they produce constitutes still today the more important limit. In fact, from the point of view of the customer who can choose between various sources of energy the photovoltaic offers some indirect advantages. Fig. 1 shows internal and external (environmental) costs of electricity production. In the context of internal costs some additional outliers on the upper range side are here excluded in the case of hydropower. The photovoltaic (PV) plants, on the cost point of view, are penalized in respect to other conventional energy resources [2]. In fact, without specific public incentives which calculate the social advantages offered by PV technology, the photovoltaic is not yet competitive with other resources. The thermal conventional technologies are actually more expensive in term of social costs, but users no directly pays this social costs that are in charge on the society.

Real resource costs should include both the private costs incurred to provide power and the external costs of damage (or deterioration in quality) to the environment caused by power generation.

Even if there is not a standard application of the external costs, their progressive introduction in the energy price evaluation should improve the possibility to use renewable sources and their efficiency on the economical point of view.

A typical approach for the evaluation of the external environmental costs applied to electric energy production is a methodology so called “impact pathway” [2] that evaluates the dispersion, deposition and effect of the pollution. This methodology summarizes the impact of the system in a money indicator of the global performance. Anyway, this method does not take into account social factors neither environmental aspect that is difficult to quantify in costs. Considering the limitations of that methodology, the evaluation of the total costs remains a useful method that still needs further improvement by means of research and development of models [3].

Already in the last twenty-years of the past century thanks to a study performed by the Fraunhover Gesellschaft - Institut fur Solarenergiesysteme (FhG-ISE) of Friburg, on behalf of the European Union some values have been supplied [4]. The job of the FhG-ISE makes reference to the existing situation in the Federal Republic of Germany in 1984 and takes in consideration the production of thermo-electrical, conventional or nuclear systems. The conclusions of the study demonstrate that, also using the prudential criteria the medium indirect labor costs associate to the fossil fuel use (converted in euro) are of the order of 0.04 €/kWh, while those associate to the nuclear are of 0.06 €/kWh. This study, for its innovative character and its importance, has been taken to model in successive analyses.

The European project THERMIE [5] leads to a cost for producing energy with fossil sources that can be estimated in 0.20€/kWh. The increase of this value can be correlated to an increase of the emissions in gas atmosphere of carbonic greenhouse gas as carbon dioxide (Fig.2). It is possible to assume that the CO_2 emission into the atmosphere will continue to increase, in the next years, with linear shape. Since the gas emissions of greenhouse gases in the atmosphere are directly tied to the monetary value of the sustainability, it can be supposed that also these costs linearly increase.

An esteem of the economic value of the sustainability for the next years can be made, starting from the economic data previously indicates, in the following way[1]:

$$S_{€} = 0.022857142 \cdot t - 45.56 \quad (1)$$

The proposed equation is based on the hypothesis that the carbon dioxide emissions will grow with the same behavior of the last twenty years. This is a conservative hypothesis, while considering the emissions of the numerous Underdeveloped Countries, the growth of CO_2 in the atmosphere could become at least of parabolic type. This would surely influence the economic value of the environmental aspects, making them to remarkably increase their value.

The evaluated sustainability costs are applied to the economical evaluation of a real hybrid plant in the following sections.

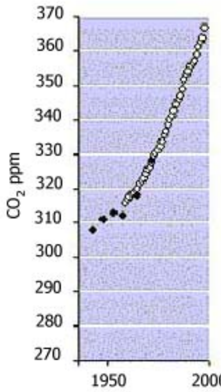


Fig.2. CO_2 emissions over past fifty years

[1] The proposed equation was derived by a linear interpolation of two economic values for sustainability, related to two different years. The used values are respectively 0.04 €/kWh for 1995 and 0.20 €/kWh for 2002.

3 Hybrid photovoltaic systems

The Fig.3 reports the schematic diagram of the hybrid photovoltaic system. These systems are profitable in isolated areas where the load demand is strongly variable. Recent studies [6] and simulations demonstrate that the advantage of hybrid generation becomes interesting, on the economic point of view, when the ratio between the peak power demand and the minimum value of the absorbed power is equal or greater than 3. However, this ratio of convenience can become lower than 3 taking into account possible difficulties due to the isolation of the plant (great distance, natural obstacles; etc.) and/or some costs associated to sustainability parameters. In addition, the presence of two different energy sources increases the reliability of the supply.

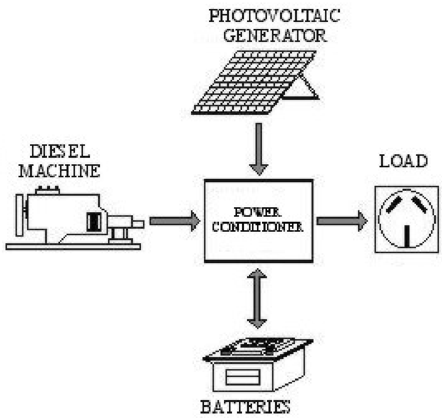


Fig.3. Schematic diagram of a hybrid photovoltaic system.

The main configurations of hybrid systems are:

a) the series type;
b) the switching type;
c) the parallel type.

The series configuration is characterized by the presence of the dc bus-bar only. The major part of the energy flow passes through the batteries with a consequent increment of the charge-discharge cycles, reducing the battery efficiency and its expected lifetime. The control system avoids battery overcharges when the produced energy is greater than the load demand, acting both on the diesel generator turn-on and on the dc-dc converter that operates as a power conditioner. The advantages of this configuration are the continuity of the supply and the possibility to supply loads with the required waveforms. The disadvantages are a reduced efficiency of the power produced by the diesel machine (that flows through two conversion stages) and a loss of supply in case of a fault in the inverter.

Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems, Chalkida, Greece, May 8-10, 2006 (pp76-82)

This latter must be designed for the peak power of the load.

The switching configuration permits, through a breaker, to supply the load from the dc busbar by means of the inverter or from the ac busbar directly connected to the diesel generator. The automatic control acts on the breaker, monitoring, on the basis of the load demand, the solar power available, the state of the battery charge and the diesel machine production. The advantages of this configuration are the possible use of the inverter for supplying loads with different waveforms and the good efficiency of the power generated by the diesel machine that flows directly to the loads. The disadvantage is a momentary interruption in the load supply during the breaker switching. In this case also, the inverter must be sized for satisfying the peak power of the load.

The parallel configuration provides the supply by both the sources in an independent (for low-medium value of the power absorbed by the load) and contemporaneous (for high value of the power absorbed by the load) way. The system control optimizes the ac-dc converter operation synchronizing the voltage on the ac bus-bar with the one generated by the diesel machine. This configuration presents the main advantage that the load power demand can be greater than the rated power of the photovoltaic and diesel generator. Then, this solution requires a lower component sizing than the previous recalled configurations, in particular for batteries, converter and diesel machine. On the contrary, a more sophisticated control and the condition of a fixed voltage waveform for the load supply at the ac-dc converter output, represent the burden of this solution.

4 Example of application

In the following the problem of design a real plant for electric power generation is summarized [3]. This design concerns the feasibility and the realization study of the photovoltaic hybrid plant of a mountain hut in the Lombardia Alps (Italy).

This hybrid system has to meet the following requirement:

- reduce the run-time, and then the cost regarding fuel and maintenance, of the diesel generator (Gen-Set) currently used;
- have an electric power generation system that respects and protects, as far as possible, the mountain environment where the hut is located;

have a system able to control and monitoring, from a remote station, the hybrid photovoltaic plant (and/or more plants positioned in different places).

4.1 Radiation data

The radiation data of the hut site are reported in Table I. In light grey are indicated the hut opening months. The first column shows the irradiation for square meter evaluated on horizontal surface for a typical day in any month of year. Starting from this data it is possible to evaluate the daily irradiation value on an inclined PV array [3]. The optimum inclination for the PV array in the site corresponds to a tilt angle of 40° and an azimuth angle of 0°. The real inclination used, imposed by the provisions on the environments impact, is 20° of tilt angle and 70° degree of azimuth angle that corresponds to the installation of the photovoltaic modules on the hut roofing; the corresponding irradiation is indicated in the second column of Table 1.

Table 1. Daily Irradiation Of The Hut Site, Evaluated On The Horizontal Surface And In The Real Condition.

month	RADIATION ON THE HORIZONTAL SURFACE [KWh / m² /day]	RADIATION TILT 20° AZIMUTH 70° [KWh / m² /day]
Jan	1.35	1.44
Feb	2.40	2.62
Mar	3.50	3.69
Apr	4.75	4.85
May	5.33	5.33
Jun	5.84	5.77
Jul	5.96	5.93
Aug	5.30	5.39
Sep	4.60	4.87
Oct	2.90	3.13
Nov	1.70	1.87
Dec	1.26	1.39

4.2 Load data

The loads present in the hut, optimised from the energy point of view, are subdivided in two different groups:

- "Batteries loads ", powered by the batteries directly (dc loads V_{dc}), or by the inverter (low power ac loads V_{ac}), as lights, refrigerator, alarms, etc.. The required total energy per day is 15.2kWh/d;
- "Direct loads" powered directly by the diesel machine, including dishwasher, hot plate and microwave oven, for a total of 13.6kWh/d.

Furthermore the dc loads are subdivided in primary e secondary loads, taking into account the importance of them associated to the plant work and the safety.

4.3 The photovoltaic hybrid system

The photovoltaic array is designed, starting from irradiation, load and PV electric characteristic data, for a maximum power of $4kW_p$. This power is

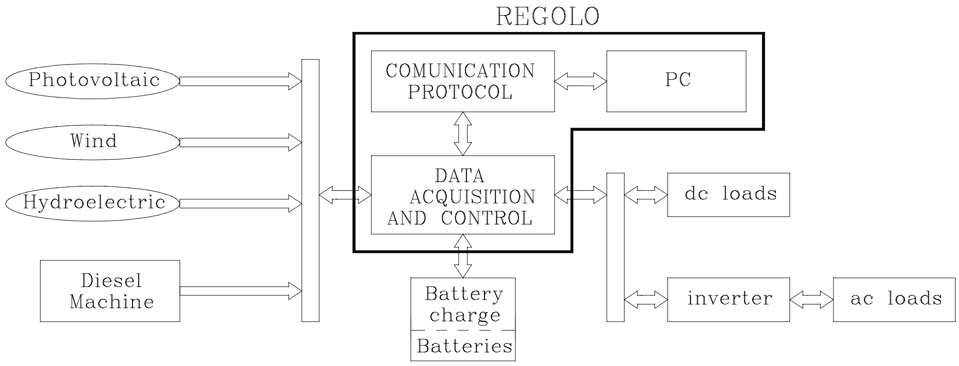


Fig.4. Schematic diagram that represents an hybrid system with the control and monitoring system.

obtained using 72 PV modules fixed on the hut roof, and 8 PV modules of $50W_p$ each one, fixed on the vertical wall of the south front of the house. The 8 PV modules fixed on the front serve to keep charged the batteries in the wintertime, when the primary 72 PV modules on the roof could be covered with snow. The battery rank is designed to power all the dc and ac loads for 4 days during low-irradiation or no-sun period. Instead, the diesel generator allows both to charge the battery and to supply directly the ac users for longer no-sun periods (more then 4 days).

Taking into account the total consumption of energy related to battery loads (631Ah/day), considering the energy received during the month with the lowest sunshine (4.87kWh/m²/day) and considering a reduction coefficient of the 20% on the estimate data, the photovoltaic system is be able to produce an energy contribution of 69% (434Ah/day) of the batteries energy consumption.

The inverter for the power supply of the battery loads have nominal power of 5kW, 150% overcharge for 3s., and efficiency of 90%.

Using the hybrid system it is possible to reduce the diesel generator run-time from about 16h/day to 2h/day. This means that we can save about 14 h/day of diesel generator work that correspond to about 1400 h/year and to approximately 1400 liter of diesel fuel saved per opening season.

From the environmental impact point of view this means that the emission of carbon dioxide (CO_2) in the atmosphere is cut down of about 3 tons/year.

4.4 Control and Monitoring System

The configuration of this HIHS system is a mix of all the previous described configurations. The schematic diagram of the system is reported in Fig. 5. It is possible to note that the interaction between the generators (photovoltaic and diesel), the batteries and the loads is regulated by the data acquisition and control system that optimizes the use of the energy sources and the operation of the batteries. The loads are divided on the basis of their importance for the customer needs and the safety. In case of energy deficit and battery low charge level, the control device provides a scheduled load shedding for assuring the supply of the main loads only. Moreover, it is possible to transfer all the data to a personal computer (PC) in a remote control station.

Other important characteristics of the control system – described in [3] - are summarized in the following:

- The possibility to measure electric quantities (voltages, currents, frequency of the ac supply) on the plant and external quantities useful for the efficiency optimization.
- The regulation of the battery power flow to avoid life time reduction or operating conditions that can decrease the battery reliability.
- The definition of a protection and warning system able to prevent fault conditions.
- The possibility to check the present operation of the plant and the previous data recorded in the memory, together with the possibility to set the warning thresholds. These actions can be carried out both on site and on a remote station by means of a communication protocol.
- The capability of the system to transmit warning to a remote station, pointing out the anomalous operation of the plant.
- The presence of a local memory card for environmental and electrical data collection and processing.

Thanks to these properties on the collected data, it is possible to manage the HIHS and to modify, if necessary, the control algorithm in order to optimize the system work with respect to the local conditions.

5 Economic analysis

Scope of this section is to estimate the cost and therefore the economic convenience to install a photovoltaic system in place of electricity-generating groups for an isolated load. The analysis is performed comparing the hybrid plant (HIHS) shown in Section 4 and the same plant, which uses as energy source a stand-alone Generator Set (GS). The produced kWh cost is calculated using the Unit Electricity Cost (UEC) method referring to the two plants solution analyzed.

5.1 Evaluation of the hardware plant's cost

The first step for the economic analysis consists in the evaluation of the overall costs of the two plants under examination: GS type and HIHS type.

Diesel generator, fuel and maintenance costs. The used GS has and indicative cost of about 5100 €. Focusing on the fuel costs, in the GS plant the generator works 16 hours per day for 110 days. The fuel consumption is about 1 l/h and its cost is about 1.02 €/l. The yearly fuel cost amounts to 1795.20 €. In the HIHS type plant the diesel generator works only 2 hours per day with an yearly fuel cost of 224.40 €. The diesel generator maintenance costs are calculated on the number of maintenance events per year. Maintenance has to be done every 150 working hours for the diesel generator. As a result the GS type plant needs 11 maintenances per year with an overall cost of 5500 €, while HIHS type plant needs only 2 maintenances per year with an overall cost of 1000 €.

Photovoltaic modules. The system under analysis is built of 80 modules of 50Wp each made up of 36 solar cells. The mean price of each module is 171 €. So the PV modules cost is about 13700€. The PV have to be installed on support structures in order to obtain the design inclination, for a total price of 878€.

Batteries. The used batteries has a capacity of 3100 Ah and the cost is about 6800 €. The chemical protection system price is assumed equal to 1275€. The inverter has an overall cost of 2346€. The battery charger on the basis of the market analysis is evaluated in about 850€.

Installation. The evaluation of the installation costs is done with the labor price taken from Milan's Chamber of Commerce in 2001. It is assumed that three persons compose the team involved in the installation of the plants. The installation of the GS type plant can be done in about five working days, three of them in which is present the whole team and two of them in which the most qualified worker is not present. The HIHS type plant needs, for installation, the presence of the whole team for twelve working days.

In Tables 2 and 3 the costs of the two considered plants are summarized. A comparison of the two tables shows that the installation of a HIHS plant needs a sum of money larger than the GS one. This is due substantially to the PV modules costs. This amount, despite its value, will be reduced in the next years because of the increase of the number of PV producer company. This lead to a greater market competition, which involves costs reduction.

5.2 Produced energy cost

The analysis is completed with the evaluation of the cost of the produced energy by the real plant, using the Life Cycle-Costing (LCC). The parameters for LCC evaluation are [6]:

- period *n*: the period of time, n, during which the system is under analysis, that is, the greatest expected lifetime of the component;
- inflation *i*;
- discount rate *d*: the applied active rate on *d*=2-5%;
- cost of money and the overall hardware and installation costs;
- benefits: in particular the economic value due to the reduction of greenhouse gases emitted in the atmosphere;
- operation and maintenance costs;
- fuel costs;
- substitution costs of every part at the end of its operative life.

Table 2. GS plant costs

Installation	[€]	1871
Hardware	[€]	6138
Operation and mainteinance	[€]	7295
Total	[€]	15305

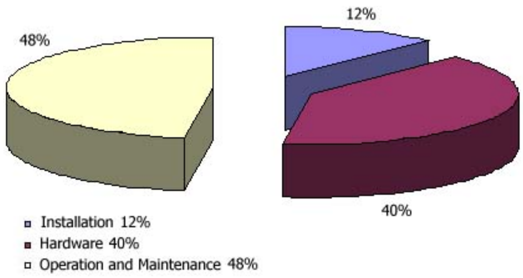
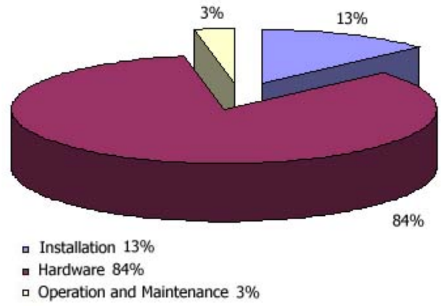


Table 3. HIHS plant costs

Installation	[€]	5227
Hardware	[€]	32838
Operation and maintainance	[€]	1224
Total	[€]	39290



The LCC evaluation needs that all costs and benefits, present and future, are brought back to present value or Present Worth (PW). The present value of the amounts is calculate, as function of the period of the payment, using two different updating factors:

- single payment $PW_r = C_r \cdot \left(\frac{1+i}{1+d}\right)^N = C_r \cdot P_r$ (3)
- annual payment

$$PW_a = C_a \cdot \left(\frac{1+i}{1+d}\right) \cdot \left(\left| \left(\frac{1+i}{1+d}\right) \right|^N - 1 \right) \Big/ \left(\frac{1+i}{1+d} - 1 \right) = C_a \cdot P_a \quad (4)$$

where C_r is the cost at year r and N is the expected life-time of the part. The C_a is the recurrent annual cost. The sum of all PW gives the LCC. The produced energy cost is so calculable by means of the Annualized life-cycle costing (ALCC):

$$ALCC = \frac{LCC}{P_a} = \left[\frac{€}{year}\right] \quad (5)$$

which leads to the Unit Electricity Cost (UEC) by means of the annual produced energy given by the ratio between the ALCC and the annual energy E produced by the plant:

$$UEC = \frac{ALCC}{E} = \left[\frac{€}{kWh}\right] \quad (6)$$

Table 4 and Fig.5 show the UEC evaluated in different conditions. These conditions differs each other only for the way of evaluation of the sustainability. Three different sustainability values are proposed: a null value of the environmental aspects, a constant value [5] and a linear increasing value as proposed by equation (1).

The UEC reported in Table 4 is a very significant indicator for performance evaluation of energy generation systems and gives, practically, the kWh generated cost. In particular, the UEC for different plant type with a range of ±20% around the normal produced energy, and with different evaluation of the sustainability costs are reported in Fig.5.

6 Conclusions

The paper present an economic study of possible photovoltaic hybrid systems studied for improving sustainable energy development. The result is the significance and validity of hybrid systems in isolated plants where solar energy is effective and the respect of the environment is important.

The proposed method represents a valid reference determining the economic evaluation of a stand-alone PV system where the following factors can be highlighted:

- the social and environmental benefits due to non polluting and no noise operation of the PV system, together with the possibility to integrate the PV modules in the building structure;
- the independence form the fuel use.

Taking into account these costs, meanly related to the sustainable development, the economical factor as UEC become of interest in PV application for isolated users.

Table 4. HIHS unit electricity cost

Opening period [days]	Energy consumption [kWh/year]	UEC without sustainability [€/kWh]	UEC with constant sustainability [€/kWh]	UEC with linear sustainability [€/kWh]
88	2534	0.98	0.73	0.46
110	3168	0.79	0.59	0.37
132	3802	0.65	0.49	0.31

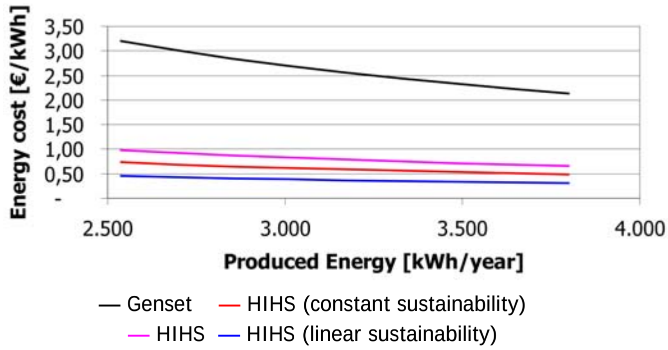


Fig.5. Energy costs.

References:

[1] Landau Network-Centre Volta School International UNESCO Science for the Peace. *Energetic political and Strategies for the future: Scientific, Technological and Economic aspects* Vol.1 Como - Villa Olmo Settembre 1998 (In Italian)

[2] European Commission, *ExternE-Externalities of Energy*, Vol. 10: National Implementation , EUR 18528, Directorate-General XII, Science, Research and Development, Luxembourg (1999).

[3] W. Dalbon, S. Leva, M. Roscia, D. Zaninelli, Hybrid Photovoltaic System Control for Enhancing Sustainable Energy, *Proc. IEEE PES Summer Meeting*, Chicago (IL), USA, July 21-25, 2002, n.pp. 6

[4] http://members.xoom.virgilio.it/solardesign/eco_fot.html

[5] http://europa.eu.int/comm/dg12/joule1.html

[6] T. Markvart, *Solar Electricity*, England: John Wiley & Sons, 1997