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SOLAR 1.1 software: a case study of a chicken farm illumination project

Aplicativo SOLAR 1.1: estudo de caso do projeto de iluminação de uma granja

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Abstract

The aim of this paper is to describe the use of SOLAR 1.1 software to design an illumination system for a chicken farm. This software version also helps carry out the economic analysis for grid-connected or stand-alone photovoltaic systems for choosing practical values of the investment rate and annuity factor and calculates the payback period of investment in the photovoltaic plant.

Key words: Economic analysis. Photovoltaic cell. Photovoltaic systems. Solar radiation.

Resumo

O objetivo deste artigo é descrever o uso do aplicativo SOLAR 1.1 para projetar um sistema de iluminação para uma granja. Essa versão do aplicativo também possibilita realizar a análise econômica de sistemas fotovoltaicos conectados à rede elétrica ou isolados para escolha de valores práticos de taxa de investimento e fator de anuidade e calcula o período de retorno do investimento na planta fotovoltaica.

Palavras chave: Análise econômica. Célula fotovoltaica. Radiação solar. Sistemas fotovoltaicos.

1 Introduction

The fast increase of population in the world and the continuous improvement in living standards, even if in a restricted number of countries, are the causes which have raised, since the beginning of 20th century to the present, the demand for energy.

Today, the energy demand has reached a non-sustainable level with a consequent decrease in environmental quality and energy resources of the planet.

Also notably, environmental pollution is increasing along with energy production. In fact, the mechanical and thermal energies used are in great part produced by burning fossil fuels, namely petroleum, coal, and natural gas. From these resources is produced heat that can be converted into electrical or mechanical energy.

In industrialized countries, petroleum has been the most utilized source to produce energy. After the Second World War, with industrial expansion, petroleum demand duplicated due to high availability and low cost. Only in the end of 70s, after the energy crisis, was a new thinking introduced in society about the way to deal with the issue of energy. The problem of limited fossil fuel reserves and the growing attention to environmental degradation launched the use of alternative energy sources (EPE, 2008).

The heat from fossil fuels is derived from the chemical reaction of combustion in which carbon and hydrogen are oxidized. This reaction produces some dangerous substances: carbon monoxide and unburned hydrocarbons, through imperfect and incomplete combustion; sulphur dioxide, sulphuric anhydride and sulphuric acid, due to the presence of brimstone in the fuels and nitrogen oxides, through the oxidation of atmospheric nitrogen (EPE, 2008).

Another combustion product is carbon dioxide. This is an inert gas present in the atmosphere and is not dangerous for man. But it is not transparent to the infra-red radiation emitted by the Earth, so great concentrations of carbon dioxide produce the greenhouse effect and the consequent increase of the planet's temperature. For this reason, in 1997, the United Nations Framework Convention on Climate Change (UNFCCC) decided a decrease by 2010 of 5% in climate-altering emissions in the world (Kyoto protocol) (EPE, 2008).

Fossil fuels have also the characteristic of being located in concentrated form: they are found only in few parts of the planet. This is sometimes the cause of international tensions between countries that possess these sources and countries that want to acquire control over them (EPE, 2008).

A small part of energy demand is satisfied by non-emitting or low-emission sources. These are the renewable sources of energy, sources which are alternatives to petroleum and to other fossil fuels (EPE, 2008).

Renewable energy is any source of energy that can be used without depleting its reserves. These sources include sunlight or solar energy and other sources such as, wind, wave, biomass and hydro energy. These latter sources are indirectly derived from solar energy. Biomass refers to any recently produced organic matter. If the organic matter is produced sustainably, then it is considered to be a renewable energy resource (EPE, 2008).

Fossil fuels such as coal, oil and gas come from biomass that was produced in the distant past and has been transformed by geological activity. World reserves of fossil fuels are finite and are being depleted. They are therefore referred to as non-renewable energy sources (EPE, 2008).

Uranium for the generation of nuclear energy is not a fossil fuel but still requires the depletion of finite physical reserves, so it is included as a non-renewable energy source. Some geothermal resources may be regarded as renewable because they are derived from energy sources deep within the earth's interior. The energy sources are so large that the rate of depletion by a geothermal energy extraction project is negligible. Projects based on using the remnant heat stored in shallowly-placed igneous rocks may be non-renewable. However, the use of energy from such sources does not produce greenhouse gases (EPE, 2008).

Another renewable resource, tidal power, results from harnessing tidal currents, which are caused mainly by the gravitational force of the moon on the oceans as it circles the earth (EPE, 2008).

Biomass is the only renewable energy source in use that releases carbon dioxide. However the carbon dioxide emitted is balanced by the incorporation of carbon from the atmosphere into the biomass while it grows. If the biomass resource is being used sustainably, there are no net carbon emissions over the time frame of a cycle of biomass production. This could be a year for agricultural crop waste, such as bagasse, or decades for forest products. In addition, minor amounts of greenhouse gases may be created in producing the technology to transform the renewable energy resource into usable energy (EPE, 2008).

Because the use of renewable energy creates so few greenhouse gas emissions, it is an important part of the world's response to the enhanced greenhouse effect.

The sun provides the energy to heat and light the earth, making it habitable. This energy is not traded commercially and hence is not included in energy statistics.

More than 80% of the world's commercial energy comes from non-renewable fossil fuels, Figure 1 (EPE, 2008).

It is evident that to contain polluting emissions and to avoid climatic alterations it is necessary to make a greater use of renewable sources in the production of energy.

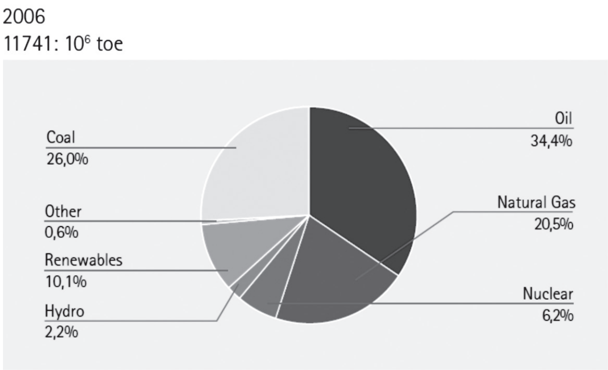


Figure 1: Share of world energy use by source (2006)
Source: Empresa de Pesquisa Energética – EPE (2008).

There are many technologies to use these sources to produce mechanical, thermal and electrical energy.

Solar energy is used to produce heat and electricity. Photovoltaic (PV) technology enables the transformation of solar energy into electric energy (NREL, 2009).

In this paper, a kind of renewable source is studied: the sun, and the technologies (photovoltaic systems) to convert solar radiation energy into electrical energy.

Renewable sources of energy are distributed almost evenly throughout the planet; so, differently from non-renewable sources, they offer the possibility of producing energy by working with local resources.

Particularly, photovoltaic energy represents an opportunity to produce electricity in all places in the world, especially in developing countries, where electricity grids are often unreliable or non-existent and making investments in grid expansion is inconvenient. Often, in remote locations, photovoltaic power is the most economic option. In addition, many developing countries have high insolation levels year-round (NREL, 2009).

Photovoltaic systems cause few environmental problems. The generating component produces electricity silently and does not emit any harmful gases during operation. The basic photovoltaic material for most common modules made out of silicon is entirely benign and is available in abundance (NREL, 2009).

One criticism of early PV modules was that they consumed more energy during their production than they generated during their lifetime. With modern production methods and improved operational efficiencies this allegation is no longer true. The exact energy payback is obviously dependent on the available solar resource and on the degree to which the system is operational. High levels of solar irradiation and utilization factors will offer more rapid energy paybacks than if there is less sun and less usage; but, typically, energy payback will be realized within three to four years (NREL, 2009).

Moreover, in the economic remarks relative to the use of energetic sources, the caused environmental damages are not considered. If they were, the energy produced by photovoltaic as well as by other renewable sources would be more competitive in comparison with traditional non-renewable sources (NREL, 2009).

Table 1 shows applications in which photovoltaic technologies can be used.

Photovoltaic systems create no emissions in the production of electricity. Avoided emissions are a very positive aspect. A study done by Kroposki and De Blasio (2000) showed that a 10kW photovoltaic system in Colorado avoids 10,105kg in CO_2 emissions and 1,801kg in NO_x emissions.

No pollution of the photovoltaic system can be inserted in the economic analysis. The Denver Service Guideline estimated the costs associated with the production of carbon dioxide (CO_2) at 0.0088US$/kg, of sulphur dioxide (SO_2) at 1.65US$/kg, and of nitrogen oxides (NO_x) at 7.48US$/kg (EFFERT; THOMPSON, 2000).

Table 1: Applications for PV systems

Agriculture	• water pumping, irrigation • electric fencing for livestock and range management
Community	• water pumping, desalination and purification systems • lighting for schools and other community buildings
Domestic	• lighting, enabling studying, reading, income-producing activities and general increase in living standards • TV, radio, and other small appliances • water pumping
Healthcare	• lighting forwards, operating theatre and staff quarters • medical equipment • refrigeration for vaccines • communications (telephone, radio communications systems) • water pumping • security lighting
Small enterprises	• lighting systems, to extend business hours and increase productivity • power for small equipment, such as sewing machines, freezers, grain grinders, battery charging • lighting and radio in restaurants, stores and other facilities

The mean installation costs (including the devices) of photovoltaic systems were 5.7US$/$W_p$ for grid-connected systems and 13.9US$/$W_p$ for stand-alone systems in the USA (MORTENSEN, 2001). These high costs make the electricity produced by the photovoltaic plant expensive.

The panels' costs have an important influence on the final installation cost, between 40 and 75% (DELAHOY; KISS, 2000). Photovoltaic energetic sources will be a very attractive alternative when the panels' costs decrease, as is expected.

Hybrid options based on sustainable sources, mainly photovoltaic, have been studied as a solution for small rural villages' energy demand, such as in Chendo; Salawu, 1989; Dhere, 1989; Bailey et al., 1991; Song, 1994; Leitch; Van Der Linde, 1995; De Groot, 1997; Harford, 1998 and Valente; Almeida, 1998.

2 Methodology

The study presents the SOLAR 1.1 software, developed with the purpose of aiding in choosing among photovoltaic panels available commercially, including the electrical requirements calculation for the installation, applied to a case study for illumination of a chicken farm in Sao Paulo, Brazil. This new version of the program also helps to carry out economic analyses of grid-connected or stand-alone photovoltaic systems for choosing practical values of the investment rate and annuity factor, and it calculates the payback period of the investment in the photovoltaic plant.

For these evaluations, exergoeconomic modelling was used, as explained in Annex 1.

3 Project of a photovoltaic system for the illumination of a chicken farm

This section presents a project for a photovoltaic system using SOLAR 1.1 software (LARANCI et al., 2009a; LARANCI et al., 2009b).

The project objective is an electricity generator for a chicken farm located in Sao Paulo, Brazil. The electricity demand is for running the lights necessary to stir the chickens up during the night.

For this, it is necessary to produce energy to supply electricity for 232 lights of 25W each.

The projected photovoltaic plant is also compared with an alternative solution, in the form of a biogas engine.

3.1 Biogas engine case

The first solution presented to satisfy the energy demand is a biogas engine. In Table 2 all the parameters relative to the engine are shown.

The electricity production cost can be calculated through Equation (1) from these available values.

Table 2: Biogas engine

YANMAR MODELO NSB STANDARD 75	
Power	5.8kW
Biogas LHV (Low Heat Value)	22,000kJ/Nm³
Biogas Price	1.00US$/Nm³
Engine Price	US$350.00
Biodigestor Price	US$300.00
Maintenance Cost	0.01US$/kWh
System Efficiency	0.27
Electricity Rate	0.08US$/kWh

$$C_{elB} = \frac{I_{EG} + I_{BG}}{P \cdot H} \cdot f + C_{op} + C_{maEG} + C_{maBG} \tag{1}$$

Where:

C_{elB} = electricity production cost in the biogas engine system [US$/kWh];

I_{EG} = investment for the engine and generator [US$];

I_{BG} = investment for the biodigestor [US$];

P = installed power [kW];

H = equivalent period of utilisation number [h/year];

f = annuity factor [1/year];

C_{op} = operation costs [US$/kWh];

C_{maEG} = maintenance cost for the engine and generator [US$/kWh];

C_{maBG} = maintenance cost for the biodigestor [US$/kWh].

Table 3 shows the values of these parameters.

The electricity generation cost results in C_{elB} = 0.069US$/kWh.

Now the expected annual savings can be calculated through Equation (2)

$$S_{eB} = P \cdot H \cdot (P_{el} - C_{elB}) \tag{2}$$

Where:

S_{eB} = expected annual savings in the biogas engine system [US$/year];

P_{el} = electricity tax [US$/kWh].

Table 3: Assumptions

I_{EG}	investment for the engine and generator [US$]	350.00
I_{BG}	investment for the biodigestor [US$]	300.00
H	equivalent period of utilisation number [h/year]	2,5
C_{op}	operation costs [US$/kWh]	0.007
C_{maEG}	maintenance cost for the engine and generator [US$/kWh]	0.010
C_{maBG}	maintenance cost for the biodigestor [US$/kWh]	0.001
r	interest rate [%]	12
K	amortisation period [years]	1
F	annuity factor [1/year]	1.12

Substituting the values in Equation (2), the expected annual savings for the investment in the biogas electricity generator results in S_{eB} = 165.09US$/year.

So, with the biogas engine, electricity is produced at a cost of 0.069US$/kWh; and comparing this cost with that for grid electricity, 0.08US$/kWh, results in an annual benefit of 165.09US$/year.

Now, the calculation of costs and expected annual savings will be made in the case of the photovoltaic plant in order to make a comparison between the two systems and to evaluate if the photovoltaic plant can be a practical alternative for producing the energy demanded.

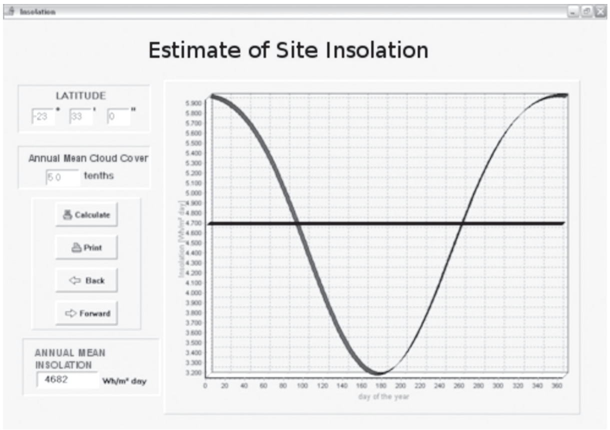
3.2 Photovoltaic system case

For the project of the photovoltaic system, SOLAR 1.1 software was used to help with the calculations.

The project begins with the calculation of the daily and mean annual insolation of the site. To be able to do this operation, the software requires the value of the latitude and of the mean annual cloud cover.

For the town of Sao Paulo these values are: latitude: 23°33'0" South and mean annual cloud cover of 5.0 tenths.

Inserting those values yields the results shown in Figure 2.



Estimate of Site Insolation

LATITUDE
-23 ° 33 ' 0 "

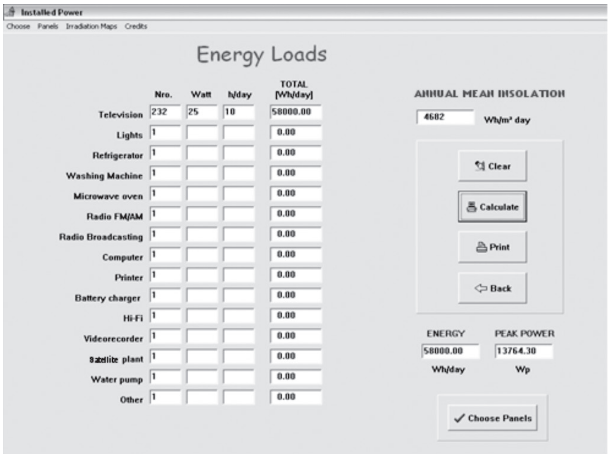
Annual Mean Cloud Cover
5.0 tenths

ANNUAL MEAN INSOLATION
4682 Wh/m² day

Figure 2: Site insolation

The estimated annual mean insolation is 4,682 Wh/m² per day; this value will be used in the following calculation for projecting the photovoltaic plant.

The energetic input data of the project are 232 lights of 25W each for an operation period of 10 hours per day (during the night). With insolation equal to the calculated value, the resulting value of peak power is 13,764.30W_p (Figure 3).



Energy Loads

	Nro.	Watt	h/day	TOTAL [Wh/day]
Television	232	25	10	58000.00
Lights	1			0.00
Refrigerator	1			0.00
Washing Machine	1			0.00
Microwave oven	1			0.00
Radio FM/AM	1			0.00
Radio Broadcasting	1			0.00
Computer	1			0.00
Printer	1			0.00
Battery charger	1			0.00
Hi-Fi	1			0.00
Videorecorder	1			0.00
Satellite plant	1			0.00
Water pump	1			0.00
Other	1			0.00

ANNUAL MEAN INSOLATION
4682 Wh/m² day

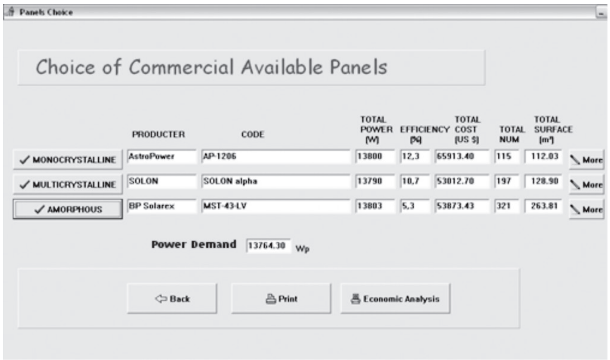
ENERGY
58000.00 Wh/day

PEAK POWER
13764.30 Wp

Figure 3: Calculation of peak power

Now it is possible to proceed with choosing the panels, clicking on the button Choose Panels.

Figure 4 shows the panels selected by the software.



	PRODUCTER	CODE	TOTAL POWER (W)	EFFICIENCY (%)	TOTAL COST (US $)	TOTAL NUM	TOTAL SURFACE (m²)	
✓ MONOCRYSTALLINE	AstroPower	AP-1206	13800	12,3	65913.40	115	112.03	More
✓ MULTICRYSTALLINE	SOLON	SOLON alpha	13790	10,7	53012.70	197	128.90	More
✓ AMORPHOUS	BP Solarex	MST-43-LV	13803	5,3	53873.43	321	263.81	More

Power Demand 13764.30 Wp

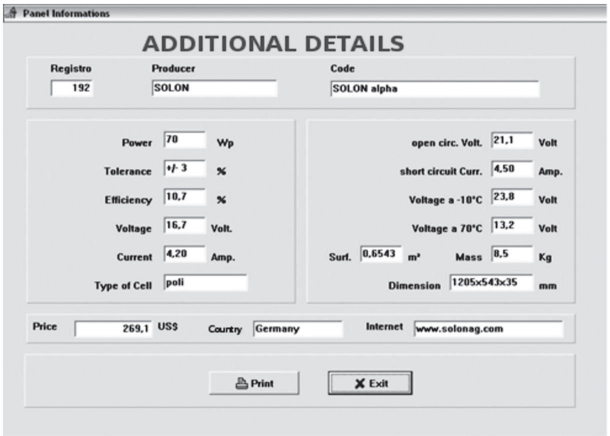
Figure 4: Choosing the Panels

The chosen panels are: monocrystalline Astropower AP-1206; multicrystalline Solon Alpha; and amorphous BP Solarex MST-43-LV.

The choice with the lowest module cost is represented by the multicrystalline type. This solution is composed by 197 Solon Alpha panels for a total installed power of 13,790W$_p$ and a total cost of US$53,012.70.

Additional details about this type of panel are shown in Figure 5.

Now the economic analysis can begin.



Registro 192
Producer SOLON
Code SOLON alpha

Power 70 Wp
Tolerance +/- 3 %
Efficiency 10,7 %
Voltage 16,7 Volt.
Current 4,20 Amp.
Type of Cell poli

open circ. Volt. 21,1 Volt
short circuit Curr. 4,50 Amp.
Voltage a -10°C 23,8 Volt
Voltage a 70°C 13,2 Volt
Surf. 0,6543 m² Mass 8,5 Kg
Dimension 1205x543x35 mm

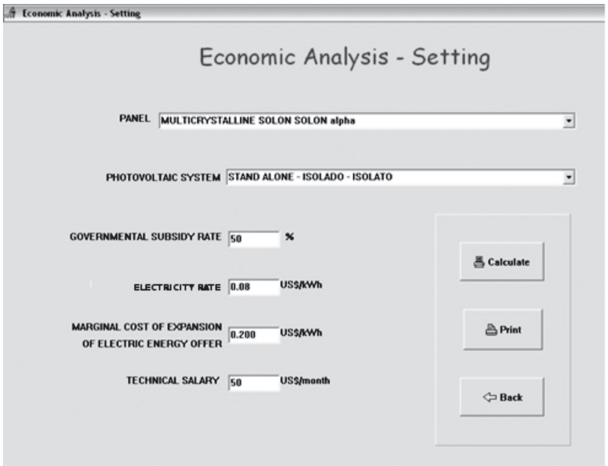
Price 269,1 US$ Country Germany Internet www.solonag.com

Figure 5: Additional details on the SOLON Alpha panel

The required photovoltaic system can be a stand-alone type. In this case a battery is necessary to accumulate the electrical energy produced during the day in order to use it during the night. For a grid-connected type, the produced energy during the day will be fed to the grid; and during the night it will be taken from the grid.

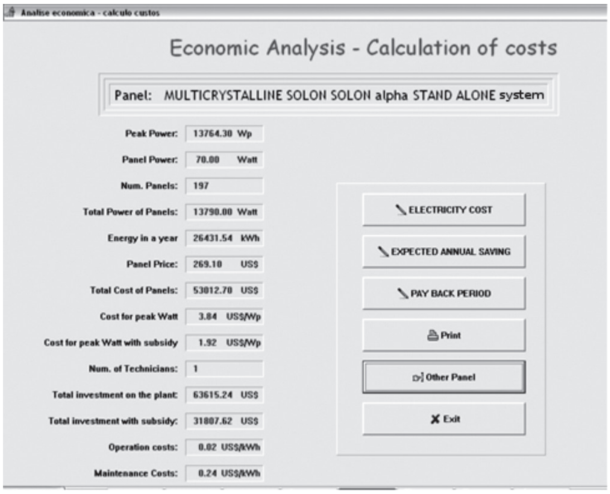
Below are the results of the economic analysis for both photovoltaic system types.

After the insertion of the information for the economic analysis (Figure 6), it is possible to do the calculations. The results are shown in the Figure 7.



PANEL MULTICRYSTALLINE SOLON SOLON alpha
PHOTOVOLTAIC SYSTEM STAND ALONE - ISOLADO - ISOLATO
GOVERNMENTAL SUBSIDY RATE 50 %
ELECTRICITY RATE 0.08 US$/kWh
MARGINAL COST OF EXPANSION OF ELECTRIC ENERGY OFFER 0.200 US$/kWh
TECHNICAL SALARY 50 US$/month

Figure 6: Information input for the economic analysis of the stand-alone PV system



Panel: MULTICRYSTALLINE SOLON SOLON alpha STAND ALONE system

Peak Power: 13764.30 Wp
Panel Power: 70.00 Watt
Num. Panels: 197
Total Power of Panels: 13790.00 Watt
Energy in a year 26431.54 kWh
Panel Price: 269.10 US$
Total Cost of Panels: 53012.70 US$
Cost for peak Watt 3.84 US$/Wp
Cost for peak Watt with subsidy 1.92 US$/Wp
Num. of Technicians: 1
Total investment on the plant: 63615.24 US$
Total investment with subsidy: 31807.62 US$
Operation costs: 0.02 US$/kWh
Maintenance Costs: 0.24 US$/kWh

Figure 7: Results of the economic analysis of the stand-alone PV system

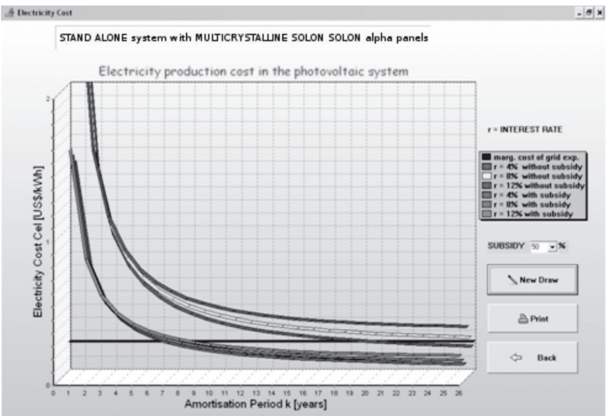
For the calculation we inserted a value of the electricity current tariff of 0.08US$/kWh and a marginal cost of expansion of the electricity offer of 0.2US$/kWh (Figure 6).

Also, the results of costs calculation are compared with the case in which there is a governmental subsidy rate equal to 50% for the installation of the photovoltaic plant (Figure 6).

The first case analysed is the stand-alone system.

Among the results shown in this window (Figure 7), there is the estimate of the total energy produced by the photovoltaic plant during a year: about 26,500kWh.

Opening the electricity cost window, the values of the electricity production cost in the photovoltaic stand-alone system for the different values of interest rate and amortisation period can be seen (Figure 8).

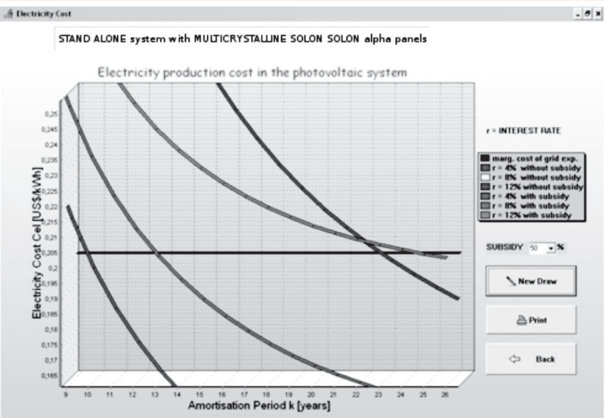


SUBSIDY 50 %

Figure 8: Electricity production cost in the stand-alone PV system

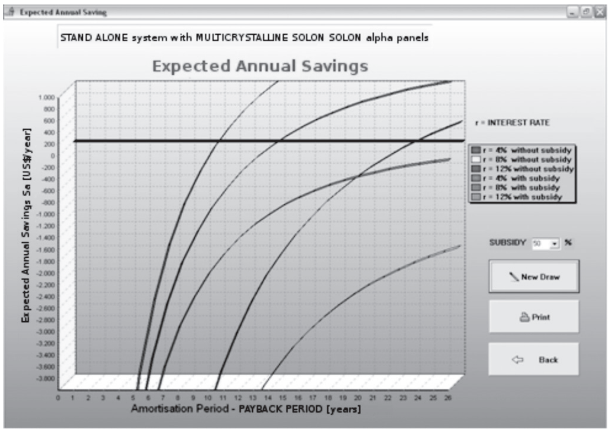
Figure 9 shows a zoomed-in view in which is possible to see the values for which the electricity production cost is lower than the marginal cost of expansion of the offer of electric energy.

Figure 10 shows the result of the calculation of the expected annual saving. In the figure there is a window of the SOLAR software showing curves of the annual saving as a function of the amortisation period. The different curves are relative to different values of the interest rate and the governmental subsidy rate.



SUBSIDY 50 %

Figure 9: Zoomed-in view of electricity production cost in the stand-alone PV system



SUBSIDY 50 %

Figure 10: Expected annual savings in the stand-alone PV system

The conditions necessary for having electricity costs lower than the marginal cost of expansion of the grid are:

- an amortisation period greater than 11 years when the interest rate is 4% and the governmental subsidy rate is 50%;
- an amortisation period greater than 14 years when the interest rate is 8% and the governmental subsidy rate is 50%;
- an amortisation period greater than 24 years when the interest rate is 4% and there is no governmental subsidy rate.

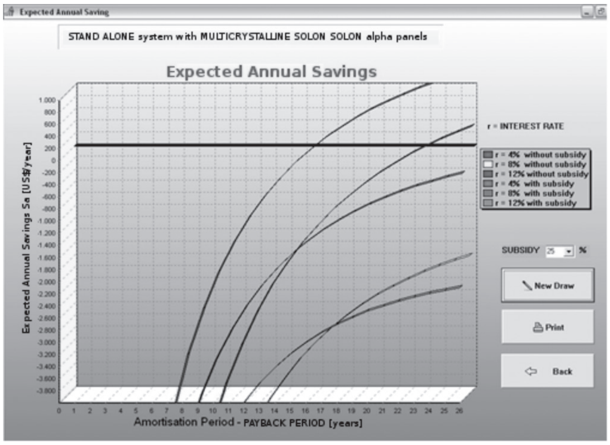
Analysing the curves, the following results emerge: to have an annual savings greater than 170US$/year, which is the value of the annual savings for the biogas engine, it is necessary to adopt:

- an amortisation period of 11 years with an interest rate of 4%, for an annual savings of 395US$/year;
- an amortisation period of 15 years with an interest rate of 8% for an annual savings of 295US$/year.

These values are both relative to the case of a governmental subsidy rate of 50%.

Without the subsidy rate, the value of amortisation period that gives an annual savings of 170US$/year is 24 years.

Figure 11 shows the expected annual savings curves when the governmental subsidy rate is 25%. In this case, to have an annual savings greater than 170US$/year, an amortisation period of 17 years and an interest rate of 4% that gives an annual benefit of 310US$/years is necessary.

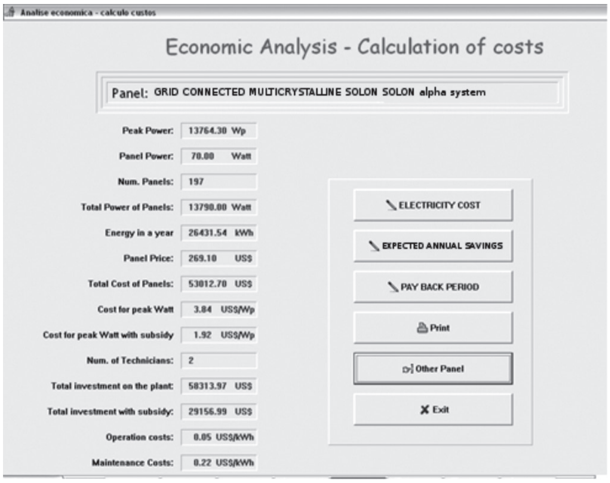


SUBSIDY 25 %

Figure 11: Expected annual savings in the stand-alone PV system with a governmental subsidy rate of 25%

Now, the results for the case of a grid-connected system will be analysed.

Figure 12 shows the results for a photovoltaic system of the grid-connected type.



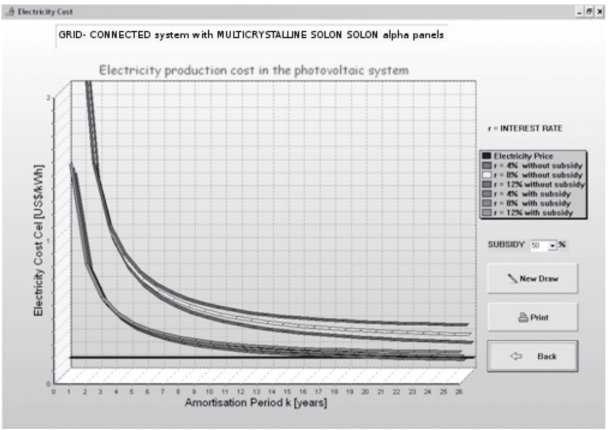
Economic Analysis - Calculation of costs

Panel: GRID CONNECTED MULTICRYSTALLINE SOLON SOLON alpha system

Peak Power: 13764.30 Wp
Panel Power: 70.00 Watt
Num. Panels: 197
Total Power of Panels: 13790.00 Watt
Energy in a year 26431.54 kWh
Panel Price: 269.10 US$
Total Cost of Panels: 53012.70 US$
Cost for peak Watt 3.84 US$/Wp
Cost for peak Watt with subsidy 1.92 US$/Wp
Num. of Technicians: 2
Total investment on the plant: 58313.97 US$
Total investment with subsidy: 29156.99 US$
Operation costs: 0.05 US$/kWh
Maintenance Costs: 0.22 US$/kWh

Figure 12: Results of the economic analysis for the grid-connected PV system

Figure 13 shows the electricity cost trend in this case.



SUBSIDY 50 %

Figure 13: Electricity production costs in the grid-connected PV system

In the diagram shown in the window (Figure 13), it is possible to see that the electricity production cost in the grid-connected photovoltaic system is always greater than the electricity rate, equal to 0.08US$/kWh. This will influence the value of the expected annual savings, which will always be less than zero (Figure 14 and Figure 15).

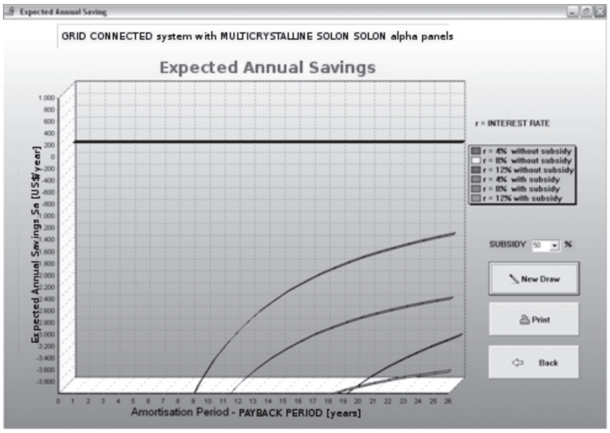


Figure 14: Expected annual savings in the grid-connected PV system

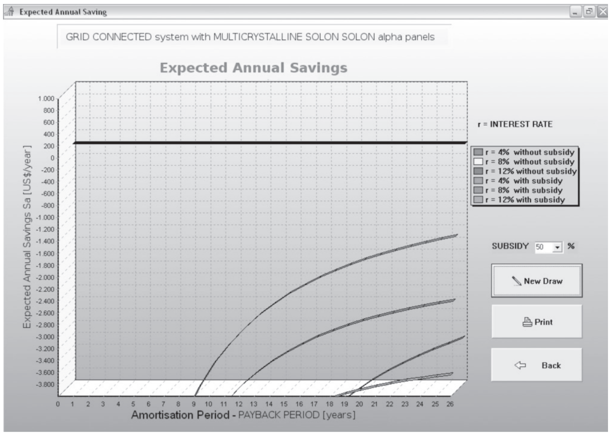


Figure 15: Expected annual savings in the grid-connected PV system

4 Conclusions

The analysis that was made in this case study gives the following results for the project case:

- a grid-connected photovoltaic system is not practical, as the expected annual savings is always negative, even when the value of the governmental subsidy rate is high;
- the stand-alone photovoltaic system represents an economically competitive alternative to the biogas engine, but only when the value of the governmental subsidy rate is high (about 50%);
- to have a higher benefit, the investment for installing the photovoltaic system requires an amortisation period longer than that for the investment for installing the biogas engine.

In conclusion, for Brazilian conditions, the use of the biogas engine to run a small electric generator can be a better solution than the photovoltaic system because its price makes the investment more practical.

The possibility of reducing the cost of panels is dependent on the government's initiative of giving incentives for the installation of photovoltaic systems.

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ANNEX 1

Electric Energy Production Cost

$$C_{el} = \frac{I_{pl} \times \left(1 - \frac{S_{ub}}{100}\right)}{E_p} \times f + C_{op} + C_{ma} \tag{a1}$$

Annuity Factor

$$f = \frac{q^k \times (q-1)}{q^k - 1} \tag{a2}$$

$$q = 1 + \frac{r}{100} \tag{a3}$$

Energy Produced

$$E_p = \frac{\eta_M}{100} \times R_A \times A \tag{a4}$$

Total Investment Cost

$$I_{pl} = C_m \times n_m + C_d + C_b \tag{a5}$$

Operation Costs

Total Investment Cost

$$C_{op} = \frac{n_{tec} \times S_{al} \times n_m}{E_p} \tag{a6}$$

Expected Annual Savings

$$S_e = E_p \times (P_{el} - C_{el}) \tag{a7}$$

Expected Annual Savings for Standalone System

$$S_e = E_p \times (C_{m_{ex}} - C_{el}) \tag{a8}$$

Daily Demand Energy

$$E = \sum_{i=1}^{k} n_i \times P_i \times H_i \tag{a9}$$

Nominal Plant Power (Peak Power)

$$P_p = \frac{E \times 1{,}000}{0.9 \times R} \tag{a10}$$

In Eq. (A10), “1,000” is a standard value of irradiance, in W/m².

Energy Produced in a Year

$$E_P = R_A \times A \times \frac{\eta}{100}$$

(a11)

Annual Insolation

$$R_A = \int_0^{365} R dt$$

(a12)

Cost of Panel in Function of the Nominal Power for: Monocrystalline Panels, Equation (A13); Multicrystalline Panels, Equation (A14); and Amorphous Panels, Equation (A15)

$$C_m = 182.322875 \times 1.013406^{P_p}$$

(a13)

$$C_m = 306.118327 \times 1.008568^{P_p}$$

(a14)

$$\log(C_m) = 0.0180791 \times P_p + 4.73025$$

(a15)

Nomenclature

A	PV panel surface, m^2
C_b	cost of battery, US$
C_d	cost of acquisition and installation of peripheral components, US$
C_{el}	cost of electric energy production in the photovoltaic system, US$/kWh
C_{el}	cost of electricity production in the PV system, US$/kWh
C_m	cost of a photovoltaic module, US$
C_{ma}	maintenance cost, US$/kWh
C_{mex}	marginal cost of expansion of the electric energy offer, US$/kWh
C_{op}	operation costs, US$/kWh
E	daily demand energy, Wh/day
E_p	produced energy in a year, kWh/year
F	annuity factor, $year^{-1}$
H_i	number of daily operation of the i-load, h/day
I_{pl}	total investment in the plant, US$
K	amortisation period, years
n_i	number of the i-load
n_m	number of module in the PV system
n_w	number of working months, generally 13
n_{tec}	number of technicians needed for the operation
P_{el}	electric tax, US$/kWh
P_i	power of the i-load, W
P_p	peak power, W_p
R	annual mean daily insolation, $Wh/m^2.day$
R	annual interest rate, %
R_A	annual insolation, $kWh/m^2.year$
S_{al}	monthly salary of a technicians, US$/month
S_e	expected annual savings, US$/year
S_{ub}	governmental subsidy rate for the installation, %

Greek symbols

η	panel efficiency, %
η_M	module efficiency, %

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