Economic Feasibility Study of Semitransparent Photovoltaic Technology Integrated on Greenhouse Covering Structures

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Abstract
This study investigates the application of semitransparent photovoltaic (PV) technology integrated on the cover of an east-west oriented greenhouse. With reference to the average greenhouse features identified through a preliminary survey over several greenhouse farms in Northern Sardinia (Italy), the study considered the application of grid-connected PV systems based on modules with light transparency ranging from 50 to 75%. A feasibility analysis was performed with different overlay levels on the roof, in order to assess their energy potential and the economic convenience of the investment. By covering south oriented roofs only, the maximum power to be installed is between 94 and 188 kWp, corresponding to a shading level respectively of 10 and 19%. Annual electricity production of PV systems considered has been estimated between 112,800 and 260,200 kWh. Considering the yearly radiation intensity examined, the potential electrical output of PV systems, for all solutions considered, is higher than the power demand of an average floriculture farm (21,600 kWh). The best economic results have been obtained with the 188 kWp PV system, with a Net Present Value amounting to 1,112,692 €, which is much higher than the investment cost (832,000 €). Payback time ranged from 10 to 13 years, respectively for the 188 kWp south oriented and for the 94 kWp PV system installed both in north and south oriented roofs.

Keywords: energy, electricity, cultivation

Introduction

Renewable energy power plants are growing up in European agriculture, contributing to a better energy self-sufficiency and environmental sustainability of farms. The installation of these power plants should be planned considering both the energy needs of the farms and their potential role as energy producers.

Among agricultural sectors, protected cultivations are notoriously a high energy demanding activity, whose production costs are strictly depending on the energy fares trend. This problem priorities the need for energy conservation strategies, by planning energy self-production and energy-saving investments. In order to preserve the advantages of greenhouse cultivation and enhance the sustainability of greenhouse production, it can be important to reduce energy consumption and to cover or partly compensate the consumed energy with renewable energy sources (Yano *et al.*, 2009). Moreover, the quota of self-produced energy exceeding the farm needs is considered by Italian norms as an economic activity connected to agricultural production, thus generating further profits through incentive fares.

In Northern Sardinia (Italy), where greenhouse farms are mainly characterised by wide-span glass structures in 70% of total greenhouse covered area, photovoltaic (PV) panels could be easily integrated in existing structures without exploiting further surfaces for agricultural activity. The consequent shading caused by the solar generator could limit plant photosynthesis and lead to problems related to crop productivity. Recent tests carried out in an experimental farm in Liguria region (Italy) have shown no significant crop productivity loss on tomato, basil, courgette and some ornamental plants cultivated with a 20% shading caused by PV modules (Minuto *et al.*, 2009). Semitransparent PV technologies, whose surface is just partially covered with solar cells, can represent the right solution for reducing their impact on the crop. These modules are transparent to light in customisable percentage, which results in a more distributed shading inside the greenhouse. In this way the greenhouse roof can be extensively covered with solar panels, limiting light radiation loss at the same time. During summer periods, integrated semitransparent PV panels could also contribute to a better thermal balance of the greenhouse, since it reduces the internal solar load and the air cooling demands.

This paper analyses the energy and economical performance of a greenhouse prototype with semitransparent PV modules integrated on the cover. The prototype has been dimensioned following the results of a preliminary field survey on greenhouse farming in Northern Sardinia. A feasibility study was performed to assess the economic convenience of a grid-connected PV system, covering less than 20% of total roof area, as to reduce the influence of shading level on crop productivity.

Materials and methods

The main features of the greenhouse sector in North Sardinia have been defined by visiting 58 greenhouse companies in 2008. The following data have been collected from each floricultural and horticultural farm: area and number of greenhouses; construction types and age; main cultivation techniques; electrical and thermal energy consumption; type of conditioning and irrigation facilities. Thus, the greenhouse type representing the average characteristics of the sector has been outlined and used for designing the PV system. The solar power generator was planned by considering two semitransparent photovoltaic modules (fig. 1), specifically designed for glass greenhouse covers, with different density of solar cells and transparency level (tab. 1): the first one with 90 Wp power module and 50% transparency level (Solarkey DG 6M24/T), the second with 45 Wp power module and 75% transparency level (Solarkey DG 6M12/T).

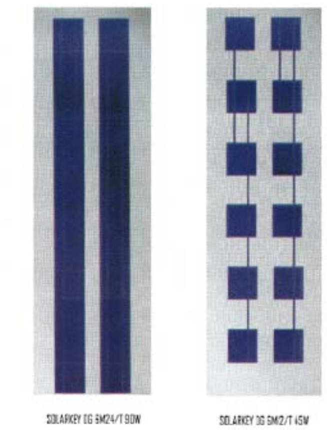

Figure 1. Distribution of solar cells on PV semitransparent modules.

Table 1. Characteristics of semitransparent photovoltaic modules considered in the feasibility study.

	SOLARKEY DG 6M24/T	*SOLARKEY DG 6M12/T*
Solar cell technology	polycrystalline silicon	
Solar cell per module (°n)	24	12
Solar cell efficiency	15%	
Cell format (mm)	156 x 156	
Module efficiency η_m	7.50%	3.75%
Maximum power (Wp)	90	45
Maximum power voltage (V)	12.12	6.2
Maximum power current (A)	7.43	
Dimensions (mm)	2000 x 600 x 5	
Transparency	50%	75%

These modules are characterised by having the same width of the common greenhouse glass panes (600 mm), thus power plant integration on the roof would be simple and cheap. Four different solutions have been outlined when planning the PV systems, depending on the module peak power (45 Wp or 90 Wp) and the percentage of greenhouse roofs covered, which can be north (N) and/or south (S) oriented roofs. The efficiency of the PV systems was calculated as function of the module efficiency (η_m) and the average overall derate factor (η_o), defined as follows:

$$\eta_o = \eta_a \cdot \eta_b \cdot \eta_c \cdot \eta_d \cdot \eta_e \cdot \eta_f \cdot \eta_g \cdot \eta_h = 0.747$$

where:

η_a = Initial light induced degradation (0.98)
η_b = DC and AC wiring (0.97)
η_c = Diodes and connections (0.995)
η_d = Mismatch (0.98)
η_e = Inverters and transformers (0.931)
η_f = Soiling (0.98)
η_g = Shading (0.96)
η_h = Temperature effect (0.92)

Shading factor (η_g) has been estimated as 0.96 for transitory shading effect caused by ridge window openings. Average annual efficiency loss is 0.4% within 20 years and 2% between year 21st and 30th, considered as the limit for PV systems lifetime. The annual radiation (R) has been calculated using the UNI10349 standard, amounting to 1853 kWh/m^{2}y for S oriented areas and 1360 kWh/m^{2}y for N oriented areas, considering a tilt angle of 25°. The average annual energy production per kWp can be calculated considering the area covered by 1 kWp (S):

$$E_{1kWp} = S \cdot R \cdot \eta_m \cdot \eta_0 \text{ (kWh/year)}$$

PV systems planned use both N and/or S oriented greenhouse roofs.

Economic analysis has considered investment unit costs of 4300 €/kWp and 4500 €/kWp, respectively for less and more than 100 kWp total power and considering the financial incentives of the national program "Conto Energia 2010". This program for stimulating PV energy production provides a feed-in tariff incentive, depending on the power and the integration factor in buildings. The 2010 incoming feed-in tariff for PV plants examined is 0.422 €/kWh, corresponding to the incentive for completely integrated PV generators, where solar panels replace parts of a building or structure. In this case, solar panels are used as greenhouse coverage instead of common glass panes. This tariff is supplied for all PV energy produced, while the energy sale tariff (0.108 €/kWh) is supplied for the quota of energy fed into grid only.

Results and discussion

Protected cultivation in North Sardinia is mainly dedicated to horticulture (22.8 ha), while floriculture occupies 9.7 ha. The most diffused greenhouse type is the wide span glass greenhouse (72%), followed by plastic type (10.5%) and tunnels (7.2%). The average covered area per farm has found to be around 6000 m^2 both for horticultural and floricultural cultivations. Soil cultivation was used in almost 80% of visited companies, while 22% used benches and only 1.7% used hydroponic technique. Heating is mainly supplied through direct-fire units consuming diesel oil (90%), while the remaining farms used heating systems with centralized hot water boilers. Internal shading curtains and energy-saving screens were installed in 22% of farms, while only 5.5% were provided with fog and fan evaporative cooling systems.

Total electricity power supply of investigated farms accounted for 620 kW, corresponding to an average of 11 kW/farm. Annual electricity consumption was estimated in 480,000 kWh_e/y for horticultural farms (2.2 kWh_e/m^2y) and 350,000 kWh_e/y for floricultural farms (3.6 kWh_e/m^2y). These values are within the average electrical consumption of a typical Mediterranean greenhouse, where power electrical demand ranges from 90,000 kWh_e/ha in greenhouses with a good climate control, to 20,000 kWh_e/ha for very low technological greenhouse structures (Campiotti *et al.*, 2008). Thermal power installed in all farms amounted to 23.9 MW_t. Thermal energy consumption was estimated through oil bills in 48.5 MJ/m^2y, reaching up to 79.1 MJ/m^2y for floricultural greenhouses.

In order to dimension the PV system, A 6000 m^2 multi-span glass greenhouse has been hypothesized, formed by two blocks east-west oriented. Each block (3000 m^2) is formed by 3 spans with pitched roof and the following dimensions: 9.60 m width, 104.40 m length, 3.00 m gutter height, 5.24 m ridge height, 5.30 m roof width, 1.30 m ridge window width, 25° roof slope. Excluding the ridge window area to allow internal ventilation, the PV modules can replace glass panes in each roof occupying a maximum surface of:

$$PV\ area = (5.30\ m - 1.30\ m) \cdot 104.40\ m = 417.60\ m^2$$

This PV area covers 75.5% of one roof. Considering the module dimensions, the maximum number of solar modules that can be installed results:

$$417.60\ m^2 / (2.00\ m \cdot 0.60\ m) = 348\ modules\ per\ roof$$

These PV modules can be placed either on the S oriented roofs only, or equally distributed between the S and the N oriented roofs, in order to have a more even internal shading area, with slightly higher solar radiation for the crop, without modifying the overall cover percentage (fig. 2). According to this, four hypothesis have been considered when designing the photovoltaic PV systems:

A. 90 Wp modules, covering all six S oriented roofs (2088 modules) corresponding to 188 kWp power;
B. 90 Wp modules, equally distributed on S and N oriented roofs (1044+1044 modules) corresponding to 188 kWp total power;
C. 45 Wp modules, covering all six S oriented roofs (2088 modules) corresponding to 94 kWp power;

D. 45 Wp modules, equally distributed on S and N oriented roofs (1044+1044 modules) corresponding to 188 kWp total power.

To calculate the different internal shading level, the roof coverage (75.5% in all design solutions) and light transparency of the modules should be considered. With the 90 Wp module (A and B solutions), characterized by 50% light transparency, the shading level referred to the entire greenhouse is about 19%: this value decreases to 10% when 45 Wp modules with 75% transparency are used (C and D solutions). Considering the energy production of 1384 kWh/kWp per year on S oriented PV generators and 1016 kWh/kWp per year for N oriented ones, the amount of electricity potentially produced by the different solutions is shown in table 2. Solutions A and B, both with S orient modules, provide 260,228 kWh/year and 130,114 kWh/year respectively. When modules are installed on both N and S roofs, the electricity production decreases of about 13%.

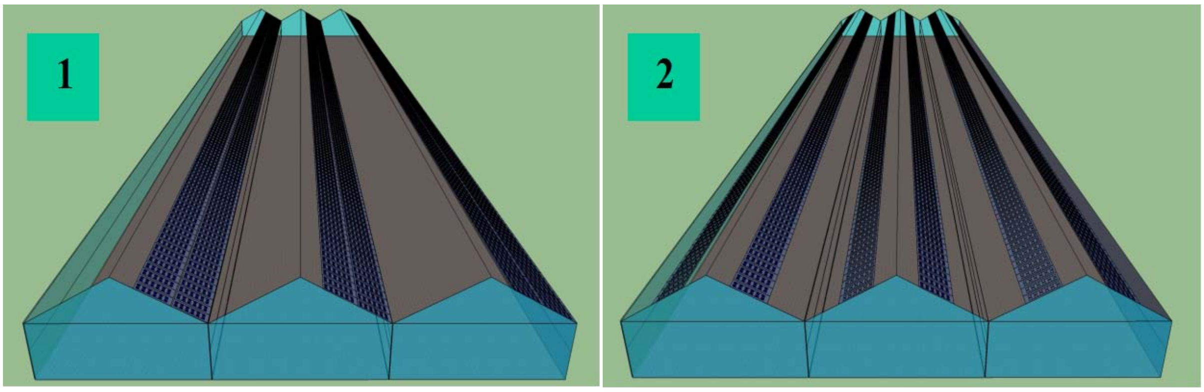

Figure 2. PV generator placing: 1) PV modules installed on S oriented roofs as solution A and C. 2) PV modules installed by equally covering N and S roofs, as solution B and D. Shading level is 10% or 19% depending on the PV module used.

To evaluate the economic results of designed PV systems (tab. 2), the following economic indicators have been considered:

- Net Present Value (NPV), calculated by the formula:

$$NPV = \sum_{1}^{n=20}\left[\frac{CF(1+i)^n(1+e)^n}{(1+r)^n}\right] - I_o$$

where:

CF = annual cash flow (€)	*r = bank discount rate (5.7%)*
i = inflation rate (2%)	*n = years*
e = energy inflation rate (3%)	*I_o = investment cost (€)*

- Internal Rate of Return (IRR), calculated as ratio between NPV and investment cost;
- Pay-Back Time (PBT), number of years needed to cover the investment cost.

NPV and IRR are evaluated within 20 and 30 years from installation. Most part of energy produced is sold to increase the overall annual income. However the PV systems supply energy for the farm too. Considering the estimated average electricity demand of 3.6 kWh/m^2y per farm, the annual energy consumption corresponds to about 21,600 kWh/y for a 6000 m^2 greenhouse. This requirement is much lower than the energy production of every PV systems considered. For example, in the A solution the electricity yearly produced by the 188 kWp system amounts to more than 260,000 kWh/y, which is 12 times more than the annual energy expenditure, providing further profits for the farm.

Investments are economically convenient for all solutions considered. NPV is always positive, showing that the investment is profitable. The highest positive NPV values are achieved with solution A and C, amounting to approximately 130% of the initial investment, while solution B and D amount up to 96%. Investments in photovoltaic energy is even more convenient if specifically applied in greenhouses: if the PV system power is less than 200 kW, the energy production is considered as connected to the main greenhouse business, with consequent tax relieves (Burchio, 2010).

IRR and PBT differ depending on the chosen solution, but always show economic convenience. A and C solutions have been found to be the most convenient ones, since NPV and IRR show the highest values compared to the other two solutions. Solution B and D (with both S and N roofs covered) allow to have a more distributed internal shadow on plants, but are slightly less convenient: covering N oriented roofs causes a solar radiation capturing decrease, which lead to a 13% energy production loss. While 1384 kWh were yearly produced by every kWp S installed, energy production decreases by 26% using N oriented roofs.

PBT of 10 years confirms the convenience of solution A and C, compared to B and D, ranging from 12 to 13 years. A payback time of 10 years is considered as a good value by PV designers, which is going to decrease in the nearly future, thanks to the constant reduction of PV technology cost. Similarly, the energy production cost is cheaper in solution A, because of the lower specific cost of the PV system (4300 €/kWp instead of 4500 €/kWp), which is connected to scale economies related to the dimension of the PV power plant.

Conclusions

Investing in PV systems installed on greenhouse roofs often focuses only on maximizing electricity production, without considering the loss in solar radiation availability for crops, when modules cover the total roof area.

This paper showed how to integrate energy on a greenhouse, limiting internal light radiation loss and avoiding significant decreases in protected crop productivity. This aim can be achieved by using PV modules specifically developed for greenhouse use, based on semitransparent technology, which can replace greenhouse glass panes. Integrated PV systems installed on S roofs provide energy amounts which are much larger than the needs of electricity of the entire farm. Installations on both S-N roofs allows a more uniform internal shading, considered on annual basis, but it makes the investment less convenient.

These power plants should be installed to provide electricity for satisfying the farm energy requirements, reduce energy costs and add further profits to the main agricultural activities, by selling the exceeding electricity produced. PV energy production in agricultural areas should be configured not as an independent business, but as a profitable activity connected to the main agriculture income of a commercial greenhouse company.

Table 2. Technical and economical comparison among the four PV systems considered.

PV system summary		***A***	***B***	***C***	***D***
Module power	***Wp***	**90 Wp**	**90 Wp**	**45 Wp**	**45 Wp**
Module light transparency	***%***	**50**	**50**	**75**	**75**
Greenhouse roofs covered	**-**	**south**	**south/north**	**south**	**south/north**
Total PV system power	***kWp***	**188**	**188**	**94**	**94**
PV area	***m^2***	**2,507**	**2,507**	**2,507**	**2,507**
Energy production	***kWh/year***	**260,228**	**225,618**	**130,114**	**112,809**
Shading level	***%***	**19%**	**19%**	**10%**	**10%**
Economic summary					
Investment cost	**€**	**832,000**	**832,000**	**434,850**	**434,850**
Feed-in tariff contribute (0.422 €/kWh)	**€**	*109,816*	*95,211*	*54,908*	*47,605*
Energy sale income (0.108 €/kWh)	*€*	*25,772*	*22,034*	*11,720*	*9,851*
Energy bills saved (0.165 €/kWh)	*€*	*3,564*	*3,564*	*3,564*	*3,564*
Total annual income	**€**	**139,152**	**120,809**	**70,192**	**61,020**
Taxes (IRES 27.5%, IRAP 1.9%)	*€*	*7,577*	*6,478*	*3,446*	*2,896*
Maintainance (1.4%)	*€*	*11,648*	*11,648*	*6,088*	*6,088*
Insurance (0.6%)	*€*	*4,992*	*4,992*	*2,609*	*2,609*
Energy deposit withdrawal (4%)	*€*	*1,031*	*881*	*469*	*394*
Withdrawal energy costs (5%)	*€*	*1,421*	*1,248*	*771*	*684*
Total annual costs	**€**	**26,669**	**25,247**	**13,382**	**12,671**
NPV 20 years	**€**	**1,112,692**	**805,024**	**566,619**	**412,785**
IRR 20 years	**-**	**1.34**	**0.97**	**1.30**	**0.95**
NPV 30 years	**€**	**1,096,183**	**772,072**	**597,393**	**435,338**
IRR 30 years	**-**	**1.32**	**0.93**	**1.37**	**1.00**
PBT	***years***	**10**	**12**	**10**	**13**
Energy production cost	***€/kWh***	**0.249**	**0.281**	**0.256**	**0.289**

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