Dimensioning and Efficiency Evaluation of Hybrid Solar Systems for Energy Production

S. Elia, Ph.D. and V. Tiberi
Department of Electrical Engineering
University of Rome "Sapienza"

ABSTRACT

Hybrid panels (HY) for joint production of thermal and electrical energy are available on the market. The main contribution of this work is to evaluate the performance of hybrid systems and to determine the field of application. Mathematical models of panels are used to evaluate thermal and electrical behaviour. Software produced by the authors calculates the energy production of these devices in several operating situations; a comparison to that of photovoltaic (PV) and thermal (TH) systems is performed. Moreover, the economic validity of such an investment is evaluated. Finally, a simplified criterion has been developed to calculate the best subdivision of the available deployment surface among TH, PV and HY panels.

INTRODUCTION

Total energy efficiency of a photovoltaic (PV) panel is very low, so a class of devices has been developed that provides electric energy as a common PV module, but at the same time also provides thermal energy thanks to a fluid that refrigerates the cells. As a fallout, this mechanism reduces the cell's temperature to increase the electric efficiency.

Thanks to this cogeneration technology, there are also some technical and practical improvements:

- The total surface area required for installation is less than if the units were installed separately;

- Hybrid panels provide architectonic uniformity when they are set on a roof;

- PV and thermal (TH) technologies use different parts of the solar spectrum. The TH one utilizes the infrared wavelength, while PV utilizes the visible wavelengths. The HY technology is also a cheap way to exploit the infrared radiation in photovoltaic plants; the alternative system would be the expensive triple junction PV device.

- Common costs, such as installation costs, are reduced.

The PV and TH components are assembled as shown in Figure 1.

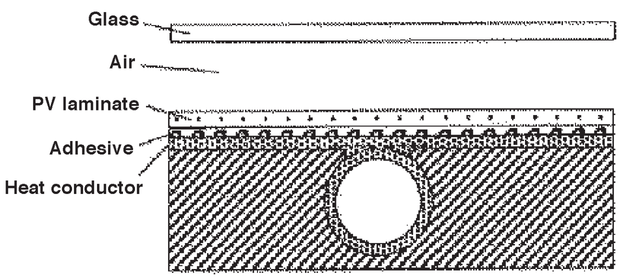

Figure 1. Constructive layout of the hybrid panel

The environmental benefit is proportional to the produced energy, assuming it succeeds in replacing energy otherwise supplied by conventional sources. Renewable energy avoids the use of primary energy and the consequent environmental impact increase. The equivalent of 2,56 kWh of fossil fuel has to be burned to produce 1 kWh of electric energy and consequently 0,53 kg of CO_2 are emitted (with an electric generation efficiency of 0.39). Supposing that a conventional thermal system had an efficiency of 85%, the equivalent of 1,17 kWh of fossil fuel is burned every thermal kWh produced. If methane is used 0,23 kg of CO_2 are emitted for every thermal kWh. If that energy was produced by the hybrid technology, the emission of 0,76 kg of CO_2 for every electric and thermal kWh will be avoided.

Mathematical Models of the PV, TH and HY Panels

A simplification of Duffie and Beckman's model [2] was made to evaluate photovoltaic system variables by a computer simulation. The analysis is performed under the hypothesis that PV cells always operate at the maximum power point using the maximum power point trackers (MPPT); by this statement, the number of equations of the model can be reduced to two (see equations 1 and 2). These equations links the temperature and the efficiency of panels.

$$T_C = T_a + \left(\frac{P\tau\alpha}{U_L}\right) * \left(1 - \frac{\eta_{mp}}{\tau\alpha}\right) \quad \text{(Eq 1)}$$

$$\eta_{mp} = \eta_{mpref} = u_{P,MP}\,(T_C - T_{ref}) \quad \text{(Eq 2)}$$

A C++ program was elaborated to calculate the cells temperature (T_c) and their efficiency (η_{mp}) and to verify the correctness of the simplified model. Fundamental input variables are: solar power (P) and ambient temperature (T_a).

The *Hottel Whillier* thermal model has been used for TH collectors [2] without any modification. The output, evaluated by this TH model, consist of: average temperature of the solar collector plate (T_{pm}), the thermal efficiency (η_{th}) and the thermal power (P_u). Inputs are: solar power (P), ambient temperature (T_a), wind speed (V_w) and the inlet fluid temperature (T_{in}). The *Hottel Whillier* model adapted and validated for the HY technology [1], is used for HY panels. Also in this case, an open source program is used to evaluate output variables. The outputs are the thermal power (P_u); the electric energy produced (E_{el}); the thermal, electric and cogeneration efficiency (η_{th}, η_{el}, η_{co}); and the cell's temperature (T_c). For the HY model, the input variables are the same. A validation of the computer results has been performed by comparing output data with literature data [1]. Tests are performed on PV and TH systems using these models, to validate the results; the average error on temperature and efficiency is less than 3%.

Ambient temperature and other literature data are available only in the form of monthly average values. An average value shouldn't be used in a non-linear equation but an exception is made on this model.

Daily tests are performed using the proposed model, and the solution gap between results and literature data is less than 3%.

Performance Analysis of PV, TH and HY Solar System

The selected area for the analysis is situated at a latitude of 41°54′N. Hourly irradiance values for each day of the year are calculated by a program developed by the authors. Hourly temperature and wind speed values obtained in several stations set in the considered zone are used (2005 is the reference year because of a compatibility with available statistics and literature data). The software conducts hourly, daily, monthly and yearly analysis.

In the following, daily tests are performed by the simulator to evaluate the energy production and the efficiency of a HY system, for each day of the year. Moreover, daily and monthly results are compared with literature data to validate the computer simulator.

In Table 1, fundamental variables describe the three systems. The computer program can evaluate energy production by solar radiation and temperature. The software defines a reference day for each month of the year: in that day, the daily energy production and the monthly average values are equal. As an example, energy production and performances are presented for the July reference day (Tables 2, 3, and 4).

The average cells temperature in the proposed daily analysis decreases by about 11 K and the electrical efficiency increases by about 4% (with peaks of 8% in the middle hours of the day) using hybrid panels rather than the photovoltaic ones. The thermal efficiency of the HY system decreases by about 35% if compared with a thermal collector. Monthly temperature variations will be shown in the following.

The trend of the thermal efficiency with the operative conditions of TH and HY panels is shown in Figure 2.

The linear response of the hybrid panel is sloped down, and it is slightly more sloped thanks to the reduction of the overall heat loss coefficient (U_{loss}).

Daily analysis performed for all days of the year denotes a constant trend of the reduction of cells' temperature. The average value is about 10K.

The complete yearly analysis is based on monthly average inputs like available solar energy, air temperature and wind speed. Cells temperature and efficiency are pointed out for each system; results are shown in Figures 3, 4, and 5.

Table 1. Fundamental Parameters of the Three Devices

Photovoltaic panel		
T_{cNOCT}	318	K
τ	0,95	-
α	0,95	-
$u_{V,oc}$	-0,09	V/K
V_m	26	V
I_m	4,8	A
A	0,94	m^2

Thermal panel		
N	1	-
β	34	degrees
ε_p	0,95	-
ε_g	0,88	-
k	0,045	W/mK
L	0,05	m
k_p	385	W/mK
δ	0,0005	m
W	0,095	m
D	0,01	m
A	0,94	m^2
τ	0,95	-
α	0,95	-

Hybrid panel		
N	1	-
β	34	Degrees
ε_{lam}	0,9	-
ε_g	0,88	-
k	0,045	W/mK
L	0,05	M
k_{abs}	385	W/mK
$k_{silicio}$	148	W/mK
k_{eva}	0,6	W/mK
δ_{abs}	0,0002	M
$\delta_{silicio}$	0,0004	M
δ_{eva}	0,003	M
W	0,095	M
D	0,01	M
h_{ca}	75	W/m^2K
A	0,94	m^2
τ_α	0,74	-
τ	0,92	-
η_{mpref}	0,133	-

Table 2. Hourly Performances of the Photovoltaic Panel on July 26

Photovoltaic Panel - Hourly Performances					
Hours of usefull solar radiation h(hour)	Hourly usefull solar power P(W/m^2)	Hourly ambient temperature T_a(K)	Hourly temperature of the cell T_c(K)	Hourly electric efficiency η_{el}	Hourly electric energy produced E_{el}(Wh)
1(6-7)	36	298	299	0.132	4
2(7-8)	180	298.5	303	0.130	18
3(8-9)	373	300	310	0.127	36
4(9-10)	566	301	316	0.124	53
5(10-11)	728	301.5	321	0.122	67
6(11-12)	841	304	327	0.120	76
7(12-13)	892	306	330	0.118	79
8(13-14)	877	306	330	0.118	78
9(14-15)	797	305.5	327	0.119	72
10(15-16)	659	304.5	322	0.122	60
11(16-17)	480	302	315	0.125	45
12(17-18)	283	302	310	0.127	27
13(18-19)	102	300	303	0.131	10
total	average value	average value	average value	average value	total
13	524	302.2	316	0.124	623

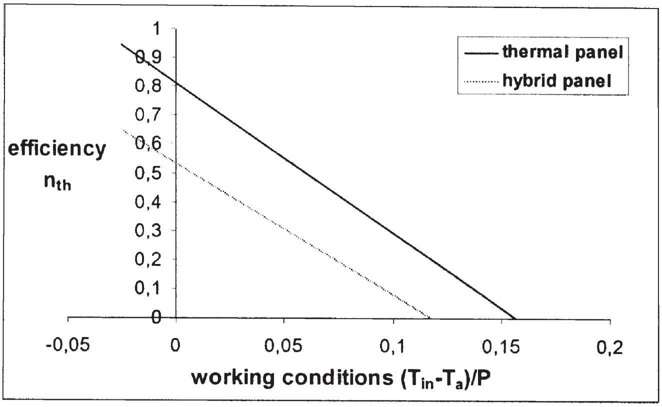

Figure 2. Thermal efficiencies by operative conditions

Table 3. Hourly Performance of the Thermal Panel on July 26

Thermal Panel - Hourly performances							
Hours of usefull solar radiation h(hour)	Hourly usefull solar power P(W/m^2)	hourly ambient temperature T_a(K)	Inlet temperature T_{in} (K)	Hourly wind speed V_w(m/s)	Usefull thermal energy Q_u(Wh)	Hourly thermal efficiency η_{th}	Average temperature of the plate T_{pm}(K)
1(6-7)	36	298	300	3.6	19	0.551	300
2(7-8)	180	298.5	300	2.6	132	0.780	303
3(8-9)	373	300	300	3	286	0.817	306
4(9-10)	566	301	300	2.8	438	0.824	309
5(10-11)	728	301.5	300	2.3	565	0.825	311
6(11-12)	841	304	300	3.8	661	0.836	313
7(12-13)	892	306	300	3.6	710	0.847	314
8(13-14)	877	306	300	4.6	698	0.846	314
9(14-15)	797	305.5	300	4.3	635	0.848	313
10(15-16)	659	304.5	300	4.1	526	0.849	310
11(16-17)	480	302	300	3	378	0.838	307
12(17-18)	283	302	300	3.6	227	0.855	304
13(18-19)	102	300	300	1.8	79	0.828	302
total	average value	average value	average value	average value	total	average value	average value
13	524	302.2	300	3.3	5354	0.811	308

Table 4. Hourly Performance of the Hybrid Panel on July 26

Hybrid panel - Hourly Performances						
Hours of usefull solar radiation h(hours)	Usefull thermal energy Q_u(Wh)	Hourly thermal efficiency η_{th}	Hourly temperature of the cell T_c(K)	Hourly electric energy produced E_{el}(Wh)	Hourly electric efficiency η_{el}	Hourly cogeneration efficiency η_{co}
1(6-7)	10	0.289	300	4	0.132	0.421
2(7-8)	84	0.498	302	18	0.131	0.629
3(8-9)	187	0.533	304	37	0.130	0.663
4(9-10)	287	0.540	306	55	0.129	0.670
5(10-11)	371	0.542	307	70	0.129	0.670
6(11-12)	437	0.552	309	81	0.128	0.680
7(12-13)	472	0.563	310	86	0.128	0.691
8(13-14)	464	0.563	309	84	0.128	0.690
9(14-15)	422	0.564	309	77	0.128	0.692
10(15-16)	349	0.564	307	64	0.129	0.693
11(16-17)	249	0.553	305	47	0.130	0.683
12(17-18)	151	0.568	303	28	0.131	0.699
13(18-19)	52	0.542	301	10	0.132	0.674
total	total	average value	average value	total	average value	average value
13	3536	0.529	305	660	0.130	0.658

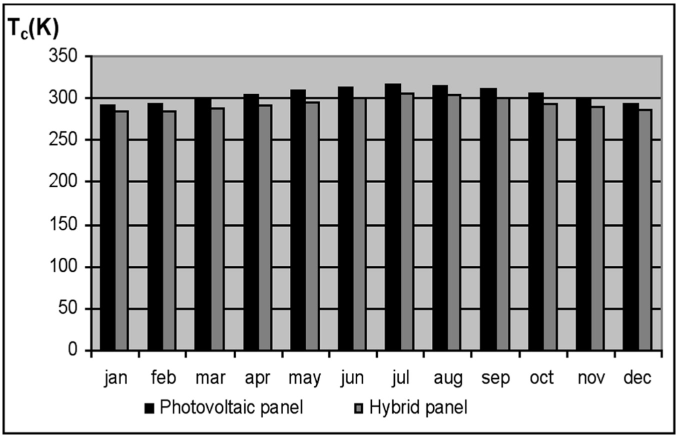

Figure 3. Trends comparison of the cells temperature between the PV and the HY panel during the 12 months of the year.

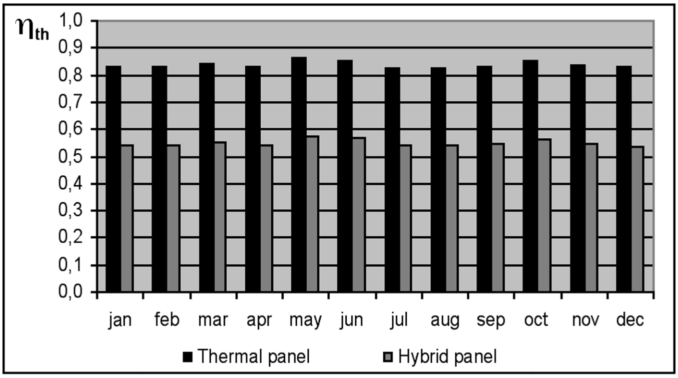

Figure 4. Trends comparison of the thermal efficiency between the TH and the HY panel during the 12 months of the year.

The cells' temperature decreases on the average about 10 K, the electric efficiency increases about 3,8%, while the thermal efficiency decreases about 35%.

A Case Study: An Application of the HY Technology in a Single-family House

First, the average energy needs for a single-family house is analyzed. Both electrical and thermal energy (thermal does not include

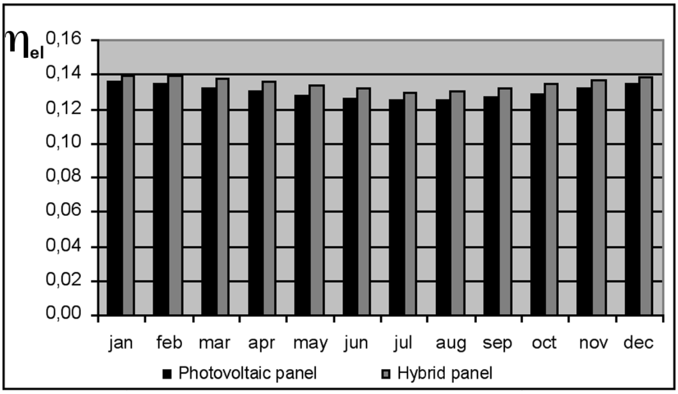

Figure 5. Trends comparison of the electric efficiency between the PV and the HY panel during the 12 months of the year.

the hot water for heating) are referred to a family unit made up of four people that live in Italy. It is assumed the house is situated at Lat. 41°54′N and the panels are tilted at 34° and oriented towards the south. The devices considered are the same as those described in the previous paragraphs (in this case the production average values calculated in the previous analysis are considered). This analysis consists of three different scenarios:

- In the first scenario, TH and PV are used to satisfy the thermal and the electrical needs. The required areas for the installation and the amount of energy that has to be provided by the auxiliary systems are calculated.

- In the second scenario, HY is used to cover the thermal needs and part of the electrical needs. The remaining electrical energy request is completely satisfied by adding PV. The required areas are calculated, and the possible integration of thermal auxiliary systems is taken into account.

- In the third scenario, it is assumed that all the thermal energy is provided by the HY panels. The area of TH panels required to produce the same amount of energy produced with the HY panels is also calculated.

The analysis provides only a preliminary dimensioning, without getting down to details. An economic analysis is also realized.

The daily thermal needs per person is thought to be 2,5 kWh for each day of the year (60 lt, 323 K). So the daily thermal needs for four people is equal to 10 kWh. Because the energy produced by the panels changes, during some months the energy produced exceeds the needs and during other months, the needs are not completely satisfied.

The plant size is calculated by choosing to completely cover the thermal needs only during the month of July (this is the month in which generally there is the peak energy production). During the other months, the energy supply is met using conventional production systems. The required area for the plant is calculated comparing the thermal needs during the month of July with the useful energy produced by the thermal collector in the same month (as shown in equation 3).

$$Needs_{th,july}=G_{july} * \eta_{th} * \eta_{acc} * \eta_{distr} * A \qquad \text{(Eq 3)}$$

In the first scenario, the required area of thermal panels is of 2,82 m^2 considering $Needs_{th,july}$=310 kWh, G_{july}=214 kWh, η_{th}=0,83, η_{acc}=0,8 η_{distr}=0,85.

During the winter months, a condensing methane boiler is used to completely cover the thermal needs.

The required area of PV panels is calculated to produce an amount

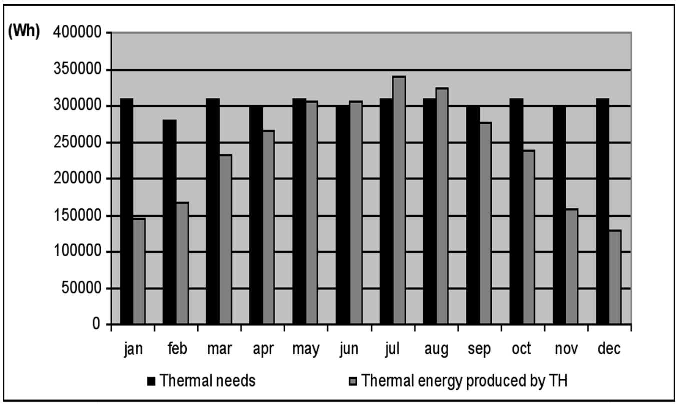

Figure 6. Comparison between the thermal needs and the thermal energy produced during the whole year.

of electric energy equal to the yearly electric needs (as shown in equation 4).

$$Needs_{elyear} = G_{year} * S * \eta_{el} * \eta_{bos} \qquad \text{(Eq 4)}$$

The required area for photovoltaic panels is calculated to be 14,1 m^2, considering $Needs_{elyear}$=2777 kWh/year (it includes the amount of energy absorbed by the feed pump of the thermal plant), G_{year}=1816 kWh/m^{2}anno, η_{el}=0,13, η_{bos}=0,8.

In the second scenario, HY panels are used. The area is calculated to completely satisfy the thermal needs in the month of July only using this device. The same equation is used for TH panels, but now the thermal efficiency is equal to 0,54. The required area of HY panels is equal to 4,7 m^2. The electrical needs are satisfied in part by the HY panels used to satisfy the thermal needs and in part by the PV panels. The required area of PV panels is calculated considering an electric need equal to the difference between the total needs and the energy produced by HY panels (η_{el}=0,135). It is equal to 9,4 m^2.

In the third scenario, the required area of HY panels is calculated considering the electrical needs and assuming that all the thermal energy they produce could be used. In this case, the area of HY panels is equal to 14,1 m^2. This area of HY also produces 9403 kWh/year of thermal energy. The area of TH panels necessary to produce the same amount of energy is equal to 9,4 m^2.

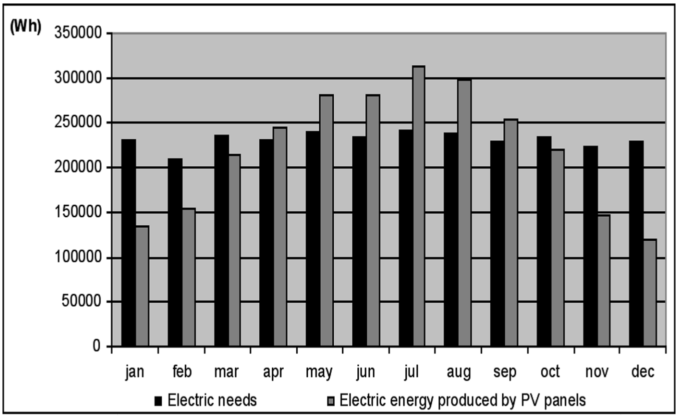

Figure 7. Comparison between the electrical needs and the electric energy produced during the whole year.

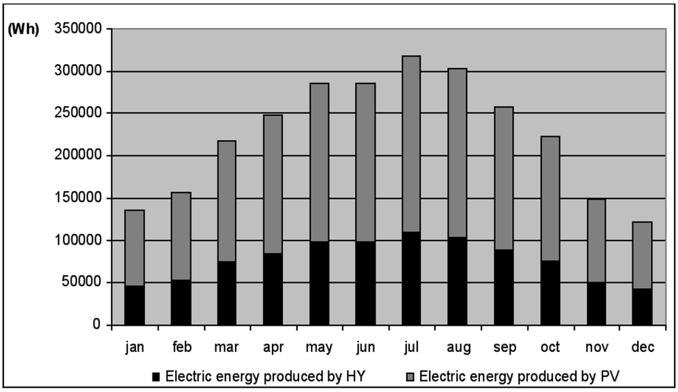

Figure 8. The electrical needs satisfied in part with HY panels and in part with PV panels.

In summary:

- In the first scenario, TH panels and PV panels are used, and the total installed area is equal to 16,92 m^2;
- In the second scenario, HY panels and PV panels are used, and the total installed area is equal to 14,1 m^2;
- In the third scenario, the total area is equal to 14,1 m^2 if only HY panels are used, whereas it is equal to 23,5 m^2 if both TH panels and PV panels are used.

So there is a reduction of 16,6% in the required area when HY panels are partially used, whereas the reduction increases to 40% when only HY panels are used.

Cost Comparison of the Generation Systems

In Table 5, the costs of the three technologies are shown. The average market price is considered for PV panels and TH panels, while the price of a batch production is shown for HY panels [4]. The cost is made up of two parts: the cost of the panel and the cost of all the other components of the system except for the panel (balance of system, BOS). Installation costs are not included.

In the first scenario, the total cost (including both panels and BOS) is equal to 13578 €, while in the second scenario the cost is equal to 14355 €. In the third scenario, the cost is equal to 18729 € if only HY are used, and it is equal to 16868 € if both TH and PV are used. So, if

Table 5. Specific cost of the three devices and of the installation components

	Thermal System	*PV System*	*Hybrid System*
Panel	180 €/m^2	3,5 €/W_p	610 €/m^2
BOS_{th}	320 €/m^2	—	320 €/m^2
BOS_{el}	—	3 €/W_p	3 €/W_p

HY panels are partially used, the price increases 5,7%. If only HY panels are used, the increase is 11%.

It is important to note that:

- The cost of 610 €/m^2 for an HY panel is referred to a limited production, while the cost of the other devices is referred to a mass production.

- The costs used do not include the installation costs of the plant. If they were considered, the increase would be lower, because the installation costs of an HY system are lower than the same costs for a combined thermal-photovoltaic plant.

A Method for the Best Distribution of Surfaces among PV, TH and HY Panels to Satisfy the Energy Needs

The main advantage of using an hybrid system is less area is required compared to a combined system, so the criterion is based on the available area and on the thermal and electrical needs. There are several parameters that have to be known to identify the best combination of the three devices.

The monthly available solar energy and the yearly average needs are required. Also, economic parameters are required according to the scheme and the units of measure in Table 6.

The installation costs are not considered as in the previous analysis. Several meaningful areas are calculated in Table 7. The best combination can be identified using these areas. The areas are calculated as follows:

$$S_1 = Needs_{elyear/}(G_{year} * \eta_{el} * \eta_{bos}) \quad \text{[Eq 5]}$$

Table 6. Required Parameters ("S" is the available area).

REQUIRED PARAMETERS	UNIT OF MEASURE	REQUIRED PARAMETERS	UNIT OF MEASURE
η_{el}	—	$Needs_{el,year}$	Wh
η_{bos}	—	S	m^2
η_{th}	—	A_{PV}	m^2
η_{thi}	—	W_{pPV}	W
η_{acc}	—	A_{HY}	m^2
η_{distr}	—	W_{pHY}	W
$Needs_{th,july}$	Wh	G_{month}	Wh/m^2

Table 7. Meaningful Areas

S_1	Area of PV panels required to cover the electric needs
S_2	Area of TH panels required to cover the thermal needs
S_3	Area of HY panels required to cover the thermal needs
S_4	Area of HY panels required to completely cover the thermal needs, partially covered by an area of TH panels equal to $(S-S_1)$
S_5	Area of Th panels required to completely covering the thermal needs partially covered by an area of HY panels equal to S_1
S_6	Area of TH panels that allows covering the thermal needs together with an area of HY panels equal to $(S-S_6)$

$$S_2 = Needs_{thjuly} / (G_{july} * \eta_{th} * \eta_{acc} * \eta_{distr}) \quad \text{[Eq 6]}$$

$$S_3 = Needs_{thjuly} / (G_{july} * \eta_{thi} * \eta_{acc} * \eta_{distr}) \quad \text{[Eq 7]}$$

$$S_4 = (Needs_{thjuly} - (G_{july} * \eta_{th} * \eta_{acc} * \eta_{distr} * (S - S_1)) / (G_{july} * \eta_{thi} * \eta_{acc} * \eta_{distr}) \quad \text{[Eq 8]}$$

$$S_5 = (Needs_{thjuly} - (G_{july} * \eta_{thi} * \eta_{acc} * \eta_{distr} * S_1)) / (G_{july} * \eta_{th} * \eta_{acc} * \eta_{distr}) \quad \text{[Eq 9]}$$

$$S_6=(Needs_{thjuly}-(G_{july} * \eta_{thi} * \eta_{acc} * \eta_{distr} * S))/(G_{july} * \eta_{acc} * \eta_{distr}(\eta_{th}-\eta_{thi})) \quad \text{[Eq 10]}$$

The best patterns and their costs can be calculated with the strategy outlined in the flow chart illustrated in Figure 9. There are several patterns proposed according to whether the conditions in the rhombus are satisfied or not.

The best solutions are shown in the rectangles of Figure 9. In each one there are the letters "T" and "E," which symbolize the thermal and the electrical needs. These two letters are followed by the devices used

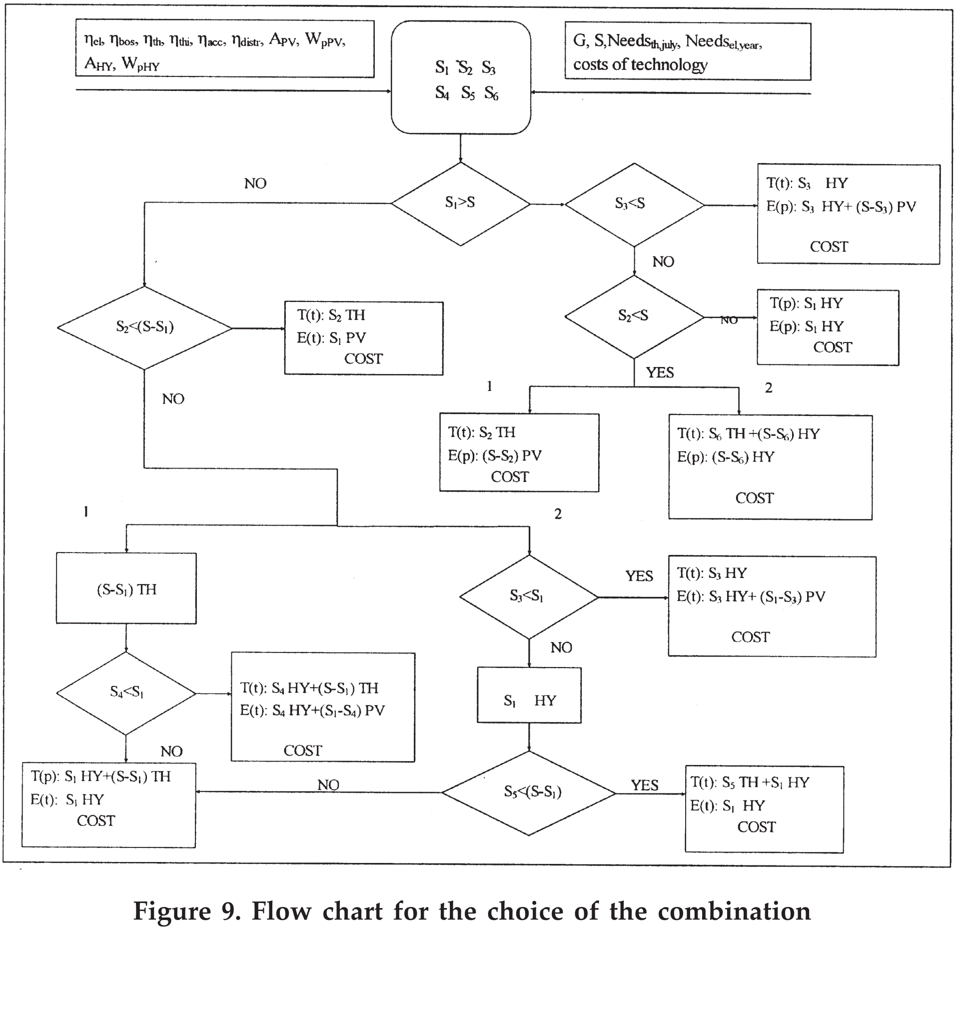

Figure 9. Flow chart for the choice of the combination

for each needs. Moreover, it is shown when needs are totally (t) or partially satisfied (p). "Totally" means that the devices produce an amount of electric energy during the whole year equal to the electric needs, while for the thermal needs, it means that the thermal energy produced during the month of July is equal to the thermal needs of the same month. For the electric energy, the yearly energetic balance with the network is equal to "0." For the thermal energy, because the month of July is generally the month with the peak in energy production, during the other months, it is necessary to use an auxiliary energy production system. This criterion is implemented with Excel software that calculates the performance and the cost of the plant. The software shows the results of all the possible combinations in nine different outputs (Figure 9).

It is possible that there can be more than one solution. In this case, more than one table has to be considered. It is important to notice that the installation of three different technologies could cause several problems, so it is better to choose the solution with the least number of different technologies when possible. Moreover, the monthly thermal needs are considered to be equal to the thermal needs during the month of July and also the electric needs are considered to be constant in each month.

CONCLUSIONS

HY panel performances have been investigated, in addition to analyzing case studies and working out a criterion to choose the best configuration of an HY solar plant. The results show that, if a hybrid technology is used, the temperature of the cells decreases by 4 K on average, with peaks of 20 K in the middle hours of the day; the electrical efficiency increases by 4% with peaks of 8%; 65% of the thermal energy produced by a TH collector in the same condition can be recovered.

The analysis of case studies point out a reduction of the used surface of 16,6% and an increase in costs of 5,7%, when HY surface is dimensioned to satisfy only hot-water needs (for mixed HY+PV plants). Moreover, tests point out a reduction of surface of 40% with an 11% cost increase, when HY surface is calculated to satisfy the electric energy needs (for entirely HY plants, with a surplus of thermal energy). The proposed criterion is a useful instrument for choosing the best solution, and it could be the basis for a general design criterion.

The use of HY panels is useful when the available area is small, especially in family home plants. To be competitive, the cost of an HY panel should vary from 444 €/m^2 and 478 €/m^2. These devices are more expensive than the traditional ones, but the cost is tolerable in exchange for the benefits. With the technology improvement and the optimization of the industrial production and distribution process, the HY system could become the optimal and cheap solution for solar energy production.

Nomenclature

T_c	temperature of the cell (K)
T_a	ambient temperature (K)
P	irradiation (W/m^2)
τ	transmission of the cover
α	absorption factor of the cell
U_L	overall heat loss coefficient (W/m^2K)
η_{mp}	maximum power point efficiency
η_{mpref}	maximum power point efficiency at the reference conditions
$u_{P,mp}$	temperature coefficient of the maximum power point efficiency
T_{ref}	reference temperature (K)
T_{cNOCT}	cell temperature at NOCT conditions (K)
$u_{V,oc}$	temperature coefficient of the open circuit voltage
V_m	maximum power point voltage in the reference conditions (V)
I_m	maximum power point current in the reference conditions (A)
W_p	Watt peak (W)
A	area of the panel (m^2)
P_u	useful power (W)
α_1	absorption factor of the plate
U_{loss}	collector heat loss coefficient (W/m^2K)
T_{in}	inlet temperature (K)
k	thermal conductivity of the isolation (W/mK)
L	thickness of the isolation (m)
N	number of the glasses
β	collector tilt (degrees)
h_w	wind heat transfer coefficient (W/m^2K)
ε_p	emittance of plate
ε_g	emittance of glass
k_p	thermal conductivity of the plate (W/mK)

δ thickness of the plate (m)
W tube spacing (m)
D outside diameter of the tube (m)
h hours of useful irradiation (hour)
G solar energy for surface unity (Wh/m^2)
h_{fi} heat transfer coefficient between the fluid and the tube wall (W/m^{2}K)
$\dot{m}$ mass flow (Kg/s)
C_p specific heat of water (J/KgK)
T_{pm} mean plate temperature (K)
σ constant of Stefan–Boltzmann
ε_{lam} emittance of laminate
k_{abs} absorber thermal conductivity (W/mK)
δ_{abs} thickness of the absorber (m)
$k_{silicio}$ silicon thermal conductivity (W/mK)
$\delta_{silicio}$ thickness of the cells (m)
k_{eva} EVA thermal conductivity (W/mK)
δ_{eva} thickness of EVA (m)
h_{ca} heat loss coefficient between the cells and the absorber (W/m^{2}K)
η_{elTc} electrical efficiency with no cooled cells
τ_a transmission-absorption factor
η_{th} thermal efficiency of the collector
η_{acc} efficiency of the accumulator
η_{distr} efficiency of the distribution system
E_{el} useful electric energy (Wh)
S area covered with photovoltaic panels (m^2)
η_{el} efficiency of photovoltaic cells in photovoltaic panels
η_{bos} balance of system
η_{thi} thermal efficiency of the hybrid panel

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ABOUT THE AUTHORS

Stefano Elia, Ph.D., is a contract professor at the Electrical Engineering Department of SAPIENZA University, Rome, Italy. He received a 5-year degree from SAPIENZA University in electrical engineering in 1999, studying in depth energy production, transportation, and utilization technologies. In 2003, he received the Ph.D. degree in electrical engineer from Sapienza University, studying computer simulation of electrical machines. Previously, he worked as electrical systems designer and energy manager consultant for many Italian companies. Dr. Steano Elia may be contacted at stefano.elia@uniroma1.it.

Vincenzo Tiberi is a student at the University of Rome for the second level degree in energetic engineering. He received his Eng. in Energetic Engineering in 2006 from the University of Rome "La Sapienza," mark 110 out of 110 *cum laude*.