DIMENSIONING AND EFFICIENCY EVALUATION OF HYBRID SOLAR SYSTEMS FOR ENERGY PRODUCTION

by

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Nowadays hybrid panels for joint production of thermal and electrical energy are available on the market. The main contribution of this work is to evaluate the performances of hybrid systems and to determine the field of application.
Mathematical models of panels are considered to evaluate thermal and electrical behaviour of the problem.
A software produced by the authors is shown that calculates the energy production of these devices in several operating situations; a comparison to that of photovoltaic and thermal systems is performed.
Moreover, the economic validity of a such investment is evaluated. Finally a simplified criterion has been developed to calculate the best subdivision of the available deployment surface among thermal, photovoltaic, and hybrid panels.

Key words: *efficiency, solar, energy, photovoltaic, thermal, hybrid, generation, simulation*

Introduction

The total energy efficiency of a photovoltaic (PV) panel is very low, so it has been developed a class of devices that provides electric energy as a common PV module, but at the same time it provides thermal energy thanks to a fluid that refrigerates the cells. As a fallout, this mechanism allows to reduce the cells temperature in order to increase the electric efficiency.

Thanks to this cogeneration technology, there are also some technical and practical improvements [1]:

- the total surface area required for installation is less than if the units were installed separately,
- hybrid panels (HY) provide architectonic uniformity when they are set on a roof,
- PV and thermal (TH) systems technologies use different part 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 PV plants, the alternative system would be the expensive triple junction PV device, and
- common costs, such as installation costs, are reduced.

PV and TH components are assembled as shown in fig. 1.

The environmental benefit is proportional to the produced energy, supposing that it succeeds in replacing the energy otherwise supplied by conventional sources.

Renewable energy avoids the use of primary energy and the consequent environmental impact increase.

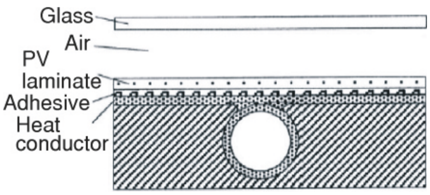

Figure 1. Constructive layout of the hybrid panel

The equivalent of 2.56 kWh of fossil fuel has to be burned to produce a 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 every thermal kWh.

If those energy were produced by the hybrid technology, the emission of 0.76 kg of CO_2 every electric and thermal kWh will be avoided.

Mathematical models of the PV, TH, and HY panels

A simplification of the 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 operates always 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, eqs. (1) and (2). These equations links the temperature and the efficiency of panels.

$$T_{\mathrm{c}} \quad T_{\mathrm{a}} \quad \frac{P\tau\alpha}{U_L} \quad 1 \quad \frac{\eta_{\mathrm{mp}}}{\tau\alpha} \tag{1}$$

$$\eta_{\mathrm{mp}} = \eta_{\mathrm{mpref}} + u_{\mathrm{P\,mp}}(T_{\mathrm{c}} - T_{\mathrm{ref}}) \tag{2}$$

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 [3], is here 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 [4] (η_{th}, η_{el}, η_{co}), and the cells 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 by means of these models, in order 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 by means of 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 of each day of the year are calculated by means of 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, due to a compatibility to available statistics and literature data). The software allows to conduct hourly, daily, monthly, and yearly analysis.

In the following, daily tests are performed by the simulator to valuate 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 tab. 1 fundamental variables that describes the three systems are shown.

The used computer program can valuate energy production by solar radiation and temperature. By means of this software is possible to define a reference day for each month of the year: in that day, the daily energy production and the monthly average values are equal. Energy production and performances are here represented for the July reference day, for example (tabs. 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 fig. 2.

The linear response of the HY panel is translated down and it is lightly more tilted 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 figs. 3, 4, and 5.

Table 1. Fundamental parameters of the three devices and respective measurement units

Photovoltaic panel			Hybrid panel		
T_{cNOCT}	318	K	N	1	–
τ	0.95	–	β	34	Degrees
α	0.95	–	ε_{lam}	0.9	–
$u_{V\ oc}$	–0.09	V/K	ε_g	0.88	–
V_m	26	V	k	0.045	W/mK
I_m	4.8	A	L	0.05	M
A	0.94	m^2	k_{abs}	385	W/mK
Thermal panel			$k_{silicio}$	148	W/mK
N	1	–	k_{eva}	0.6	W/mK
β	34	degrees	δ_{abs}	0.0002	M
ε_p	0.95	–	$\delta_{silicio}$	0.0004	M
ε_g	0.88	–	δ_{eva}	0.003	M
k	0.045	W/mK	W	0.009	M
L	0.05	m	D	0.01	M
k_p	385	W/mK	h_{ca}	75	W/m^{2}K
δ	0.0005	m	A	0.94	m^2
W	0.095	m	τ_a	0.74	–
D	0.01	m	τ	0.92	–
A	0.94	m^2	η_{mpref}	0.133	–
τ	0.95	–			
α	0.95	–			

Table 2. Hourly performances of the photovoltaic panel on July 26

Photovoltaic panel – hourly performances					
Hours of useful solar radiation h [hour]	Hourly useful 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 vlue	Total
13	524	302.2	316	0.124	623

Table 3. Hourly performances of the thermal panel on July 26

Thermal panel – hourly performances							
Hours of useful solar radiation h [hour]	Hourly useful solar power P [W/m^2]	Hourly ambient temperature T_a [K]	Inlet temperature T_{in} [K]	Hourly wind speed V_w [m/s]	Useful 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 vlue	Average value
13	524	302.2	300	3.3	5354	0.811	308

Table 4. Hourly performances of the hybrid panel on July 26

Hybrid panel – hourly performances						
Hours of useful solar radiation h [hour]	Useful 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 valure	Average value	Average value	Average vlue	Average vlue
13	3536	0.529	305	660	0.130	0.658

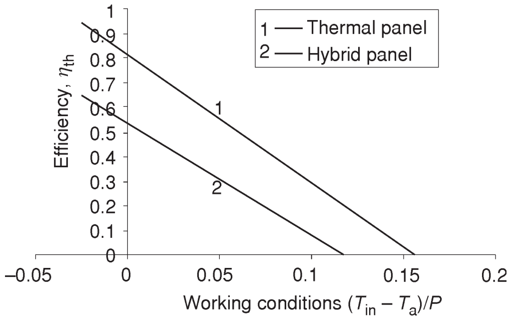

Figure 2. Thermal efficiencies by operative conditions

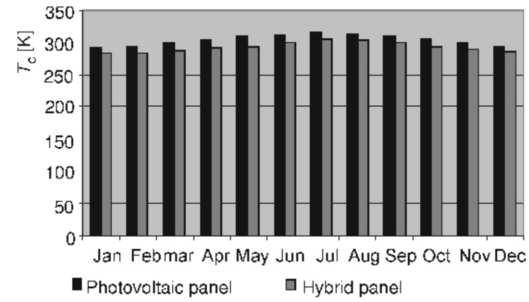

Figure 3. Comparison of the yearly trends of cells temperature for the PV and the HY panel

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 one-family house

First, the average energetic needs for a one-family house is analysed. Both electrical and thermal energy (the thermal one does not include the hot water for heating) are referred to a family unit made up of four people that lives in Italy. It is supposed that the house is situated at

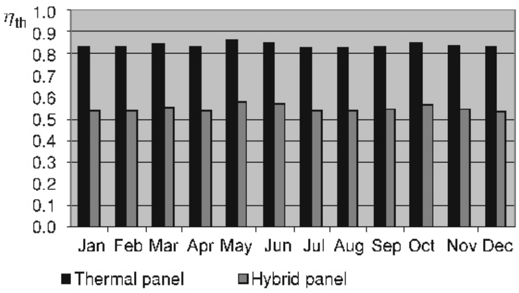

Figure 4. Yearly trends comparison of the thermal efficiency between the TH and the HY panel

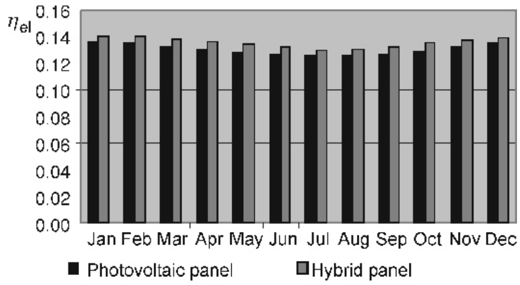

Figure 5. Yearly trends comparison of the electric efficiency between the PV and the HY panel

Lat. 41° 54' N and panels are tilted of 34° and oriented towards the south. The devices considered are the same as the previous paragraphs (in this case the production average values calculated in the previous analysis are considered). This analysis is made up of three steps referred to three different scenarios:

- in the first scenario TH and PV are used in order to satisfy the thermal and the electrical needs; the required areas for the installation and the amount of energy that have to be provided by the auxiliary systems are calculated,
- in the second scenario HY are used to cover the thermal needs and part of the electric one; the remaining electrical energy request is completely satisfied by adding PV; the required areas are calculated and the possib`le integration with thermal auxiliary systems is taken into account, and
- in the third scenario it is supposed that it is possible to use all the thermal energy 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 liters, 323 K). So the daily thermal needs for four people is equal to 10 kWh. Since the energy produced by the panels changes, during some months the energy produced exceeds the needs and during other months the needs is not completely satisfied.

The plant size is calculated choosing to cover completely the thermal needs only during the month of July (this is the month in which generally there is the peak of energy production). During the other months the energy supply is completed using conventional production systems. The requested 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:

$$Needs_{\text{th July}} = G_{\text{July}}\eta_{\text{th}}\eta_{\text{acc}}\eta_{\text{distr}}A \tag{3}$$

In the first scenario, the required area of thermal panels is of 2.82 m^2 considering $Needs_{\text{th July}} = 310$ kWh, $G_{\text{July}} = 214$ kWh, $\eta_{\text{th}} = 0{,}83$, $\eta_{\text{acc}} = 0.8$, and $\eta_{\text{distr}} = 0.85$.

In the following figs. 6 and 7 charts are shown to compare the produced energy and the demand, respectively, for thermal and electrical energy.

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

The required area of PV panels is calculated deciding to produce an amount of electric energy equal to the yearly electric needs:

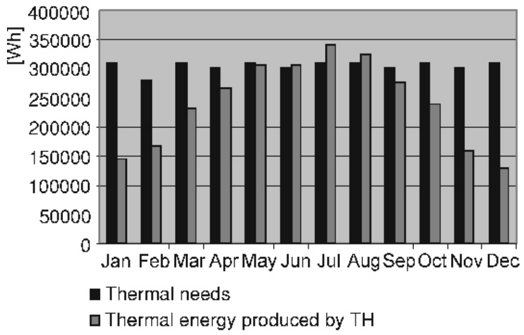

Figure 6. Comparison between the thermal needs and the thermal energy produced during the whole year

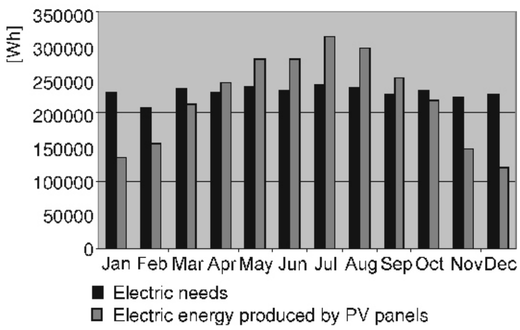

Figure 7. Comparison between the electrical needs and the electric energy produced during the whole year

$$Needs_{\text{el year}} = G_{\text{year}} S \eta_{\text{cel}} \eta_{\text{bos}} \tag{4}$$

The requested area for photovoltaic panels is calculated to be of 14.1 m^2, considering $Needs_{\text{el year}}$ = 2777 kWh per year (it includes the amount of energy absorbed by the feed pump of the thermal plant), G_{year} =1816 kWh/m^2 per year, η_{el} = 0.13, and η_{bos} = 0.8.

In the second scenario HY panels are used. Their area is calculated choosing to satisfy completely the thermal needs in the month of July only using this device. It can be used the same equation used for TH panels, but now the thermal efficiency is equal to 0.54. The requested area of HY panels is equal to 4.7 m^2. The electrical needs is 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 needs 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 supposing 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 produces also 9403 kWh per year of thermal energy. The area of TH apnels necessary to produce the same amount of energy is equal to 9.4 m^2.

In fig. 8 is shown a report of the electrical energy produced by HY panels (dimensioned to satisfy thermal needs) and by the PV panels that complete the field surface.

Summarising about panels distribution:

- 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, and
- 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 the required area of 16.6% when HY panels are used partially, whereas the reduction increase to 40% when only HY panels are used.

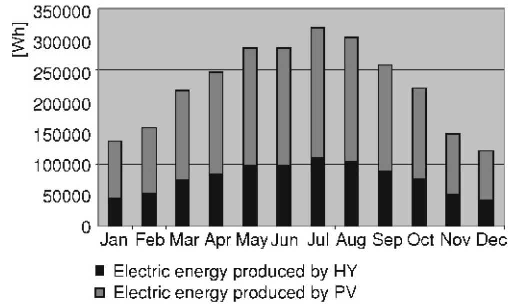

Figure 8. The electrical needs satisfied in part with HY panels and in part whit PV panels

Costs comparison of the generation systems

In tab. 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 ones [5]. 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 (BOS). Installation costs are not included.

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$_p$

In the first scenario the total cost (including both panels and BOS) is equal to 13,578, while in the second one it is equal to 14,355. In the third scenario the cost is equal to 18,729 if only HY are used, while it is equal to 16,868 if both TH and PV are used. So, if HY panels are used partially the price increase is of 5.7%, while if there is a total use of them the increase is of 11%.

It is important to notice that:

– the cost of 610 /m^2 for an HY panel is referred to a limited production, while the costs of the other devices are referred to a mass production, and
– the costs used do not include the installation costs of the plant; if they were considered the increase would be lower, since the installation costs of an HY systems 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 energy needs

The main advantage of using an hybrid system is the less area required if compared with 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 in order 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 of tab. 6.

The installation costs are not considered like in the previous analysis. Several meaningful areas are calculated: using these areas (tab. 7) the best combination can be identified.

They are calculated as follows:

$$S_1 \quad \frac{Needs_{\mathrm{el\ year}}}{G_{\mathrm{year}}\eta_{el}\eta_{bos}} \tag{5}$$

$$S_2 \quad \frac{Needs_{\mathrm{th\ July}}}{G_{\mathrm{July}}\eta_{\mathrm{th}}\eta_{\mathrm{acc}}\eta_{\mathrm{distr}}} \tag{6}$$

$$S_3 \quad \frac{Needs_{\mathrm{th\ July}}}{G_{\mathrm{July}}\eta_{\mathrm{thi}}\eta_{\mathrm{acc}}\eta_{\mathrm{distr}}} \tag{7}$$

$$S_4 \quad \frac{Needs_{\mathrm{th\ July}} \quad G_{\mathrm{July}}\eta_{\mathrm{th}}\eta_{\mathrm{acc}}\eta_{\mathrm{distr}}(S \quad S_1)}{G_{\mathrm{July}}\eta_{\mathrm{thi}}\eta_{\mathrm{acc}}\eta_{\mathrm{distr}}} \tag{8}$$

Table 6. Required parameters (now "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. Meaningfull 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 complete the covering of the thermal needs, partially covered by an area of TH panels equal to $S - S_1$
S_5	Area of TH panels required to complete the covering of the thermal needs partially covered by an area of HY panels equal to S_1
S_6	Area of TH panels that allows to cover the thermal needs together with an area of HY panels equal to $S - S_6$

$$S_5 = \frac{Needs_{th\ July} - G_{July}\eta_{thi}\eta_{acc}\eta_{distr}S_1}{G_{July}\eta_{th}\eta_{acc}\eta_{distr}} \tag{9}$$

$$S_6 = \frac{Needs_{th\ July} - G_{July}\eta_{thi}\eta_{acc}\eta_{distr}S}{G_{July}\eta_{acc}\eta_{distr}(\eta_{th} - \eta_{thi})} \tag{10}$$

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

The best solutions are shown in the rectangles of fig. 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 for each needs. Moreover, it is shown if needs is 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

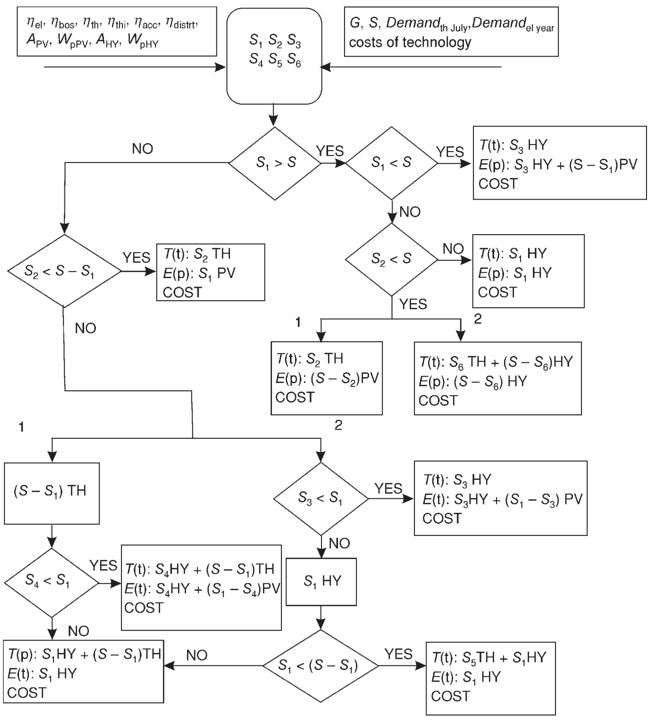

Figure 9. Flow chart for the choise of the combination

the electric energy the yearly energetic balance with the network is equal to "0"; for the thermal energy, since 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 an 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 (fig. 9).

In tab. 8 is detailed the final report for a HY solution with essential energetic and economic variables, for the whole year.

Table 8. An example of a possible solution

Table 2 – Path: Yes-No-No – Hybrid											
Months of the year	Area of HY [m^2]	Monthly average value of solar energy [Wh/m^2]	Yearly average value of the electric efficiency	Balance of system η_{bos}	Electric energy produced by HY [Wh]	Total thermal efficiency of the hybrid system	Thermal energy produced by HY [Wh]	Monthly average value of electric needs [Wh]	Balance of electric energy [Wh]	Monthly average value of thermal needs [Wh]	Thermal energy provided by the auxiliary system [Wh]
January	7	91415	0.13	0.8	66550	0.54	234973	233333	–166783	850000	615027
February	7	105665	0.13	0.8	76924	0.54	271601	233333	–156409	850000	578399
March	7	146024	0.13	0.8	106305	0.54	375340	233333	–127028	850000	474660
April	7	166702	0.13	0.8	121359	0.54	428491	233333	–111974	850000	421509
May	7	192175	0.13	0.8	139903	0.54	493967	233333	–93430	850000	356033
June	7	192007	0.13	0.8	139781	0.54	493535	233333	–93552	850000	356465
July	7	213793	0.13	0.8	155641	0.54	549534	233333	–77692	850000	300466
August	7	203561	0.13	0.8	148192	0.54	523233	233333	–85141	850000	326767
September	7	173483	0.13	0.8	126296	0.54	445921	233333	–107038	850000	404079
October	7	150034	0.13	0.8	109225	0.54	385647	233333	–124109	850000	464353
November	7	99744	0.13	0.8	72614	0.54	256382	233333	–160720	850000	593618
December	7	81544	0.13	0.8	59364	0.54	209601	233333	–173969	850000	640399
Costs [€] – 9.303 Area [m^2] – 7											

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 wreak several problems, so it is better to choose the solution with the less number of different technologies when possible. Moreover, the monthly thermal needs is considered to be equal to the thermal needs during the month of July and also the electric needs is considered to be constant in each month.

Conclusions

HY panels performances have been investigated also analysing case studies and working out a criterion to choose the best configuration of a HY solar plant. The results show that, if an hybrid technology is used, the temperature of the cells decreases of 4 K on the average, with peaks of 20 K in the middle hours of the day; the electrical efficiency increases of 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 a 11% costs increasing, 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 base for a general design criterion.

Can be certainly asserted that the use of HY panels is energetically useful when the available area is small, especially in family home plants.

The cost of an HY panel should vary from 444 €/m^2 and 478 €/m^2 in order to be competitive. These devices are more expensive than the traditional ones, but the cost is tolerable in exchange of the benefits.

With the technology improvement [6] and the optimisation of the industrial production and distribution process, the HY system could become the optimal and cheap solution for solar energy production.

Nomenclature

A – area of the panel, [m^2]
C_p – specific heat of water, [JKg^{-1}K^{-1}]
D – outside diamiter of the tube, [m]
E_{el} – useful electric energy, [Wh]
G – solar energy for surface unity, [Whm^{-2}]
h – hours of useful irradiation, [hour]
h_{ca} – heat loss coefficient between the cells and the absorber, [Wm^{-2}K^{-1}]
h_{fi} – heat transfer coefficient between the fluid and the tube wall, [Wm^{-2}K^{-1}]
h_w – wind heat transfer coefficient, [Wm^{-2}K^{-1}]
I_m – maximum power point current in the reference conditions, [A]
k – thermal conductivity of the isolation, [Wm^{-1}K^{-1}]
k_{abs} – absorber thermal conductivity, [Wm^{-1}K^{-1}]
k_{eva} – EVA thermal conductivity, [Wm^{-1}K^{-1}]
k_p – thermal conductivity of the plate, [Wm^{-1}K^{-1}]
$k_{silicio}$ – silicon thermal conductivity, [Wm^{-1}K^{-1}]
L – thickness of the isolation, [m]
$\dot{m}$ – mass flow, [kgs^{-1}]
N – number of the glasses, [–]
P – irradiation, [Wm^{-2}]
P_u – useful power, [W]
S – area covered with photovoltaic panels, [m^2]
T_a – ambient temperature, [K]
T_c – temperature of the cell, [K]
T_{cNOCT} – cell temperature at NOCT conditions, [K]
T_{in} – inlet temperature, [K]
T_{pm} – mean plate teperature, [K]
T_{ref} – reference temperature, [K]
U_L – overall heat loss coefficient, [Wm^{-2}K^{-1}]
U_{loss} – collector heat loss coefficient, [Wm^{-2}K^{-1}]
$u_{P\,mp}$ – temperature coefficient of the maximum power point efficiency, [–]
$u_{V\,oc}$ – temperature coefficient of the open circuit voltage, [–]
V_m – maximum power point voltage in the reference conditions, [V]
W – tube spacing, [m]
W_p – watt peak, [W]

Greek symbols

α – absorption factor of the cell, [–]
α_1 – absorption factor of the plate, [–]
β – collector tilt, [deg]
ε_g – emittance of glass, [–]
ε_{lam} – emittance of laminate, [–]
ε_p – emittance of plate, [–]
δ – thickness of the plate, [m]
δ_{abs} – thickness of the absorber, [m]

δ_{eva} – thickness of EVA, [m]
$\delta_{silicio}$ – thickness of the cells, [m]
η_{acc} – efficiency of the accumulator, [–]
η_{bos} – balance of system, [–]
h_{distr} – efficiency of the distribution system, [–]
η_{el} – efficiency of photovoltaic cells in photovoltaic panels, [–]
η_{elTc} – electrical efficiency with no cooled cells, [–]
η_{mp} – maximum power point efficiency, [–]
η_{mpref} – maximum power point efficiency at the reference conditions, [–]
η_{th} – thermal efficiency of the collector, [–]
η_{thi} – thermal efficiency of the hybrid panel, [–]
σ – Stefan-Boltzmann constant ($= 5.67\cdot10^{-8}$), [$Wm^{-2}K^{-4}$]
τ – transmission of the cover, [–]
τ_{α} – trasmission-absorption factor, [–]

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