International Conference on Electrical and Electronics Engineering (ICEEE) and X Conference on Electrical Engineering (CIE 2004)
Acapulco, Guerrero; Mexico. September 8-10, 2004

Energy Balance of Hybrid Systems Consisting of Wind and Photovoltaic Generators and Solar Thermal Plane Collector

Liliana Licea-Jiménez, Sergio A. Pérez-García,
Paul Horley, Jesús González-Hernández, Yuri V. Vorobiev
Unidad Queretaro of CINVESTAV
CINVESTAV-IPN
C.P. 76230, Queretaro, QRO., MEXICO

Pavel Yu. Vorobiev

Facultad de Ingeniería
Universidad Autónoma de Queretaro
C.P. 76010, Queretaro, QRO., MEXICO

Abstract **– Theoretical and experimental analysis is given of the hybrid systems made by different combinations of the water heating solar collector, wind generator and photovoltaic solar panel. It is shown that in the PV/Thermal Hybrid System, the photovoltaic panel with area much smaller than that of the collector should be used, to provide a good cooling of the panel thus increasing the electric power generated, without an essential loss in the heating water capacity of the heat collector. The Wind/Thermal System could be ideal for thermic applications: at windy weather the additional energy generated by wind unit will compensate the losses in heat production by solar heat collector. The system combining all three elements produces both electric and thermal energy; a small scale system of this kind may be useful for rural houses and/or schools, an example of such applications is given.**

1. INTRODUCTION

The hybrid systems of different kind recently became very popular in the field of renewable energy sources utilization; some of them, like PV/Thermal ones, are developed up to commercial stage (see, for example, [1-6]). It is evident that these hybrid systems *a priori* have certain advantages compared to their elements, since each one of the separate devices coupled in them has its own working conditions which quite often are contradictory (for example, the windy weather is profitable for wind generators, but it reduces effectivity of solar thermal collectors), therefore the hybrid system can be made almost independent upon the variation of these conditions, and thus more stable and reliable.

The common way to build a hybrid system is to use a combination of existing devices, which is definitely the simplest and the cheapest approach. However, this way may not be the most efficient one. The present paper intend to show that to optimize the construction and performance of a hybrid system, one has to make a special analysis of the coupling conditions of the devices used, and, in many cases, to design each device accordingly to the specific system's demands. The result will be the higher efficiency and stability of the system.

II. PRELIMINARY ANALYSIS

2.1. *Separate Performance of the System's Elements*

Here we give the basic information necessary to discuss the different combinations of the elements (for three of them, there are four possible combinations: 3 pairs, and 1 three-elements combination). A **Photovoltaic Module (PVM)** with the sensitive area A_{PV}, efficiency η_{PV} is exposed to solar radiation of power W during Δt_1 hours per day (the last parameter is averaged with account of the hourly changes in the solar position). Thus, the total energy generated by a PVM per day is

$$E_{PV} = \eta_{PV} W A_{PV} \Delta t_1 \qquad (1)$$

For a typical Si solar photovoltaic module with efficiency of 12 % and area of 1 m^2, under solar illumination corresponding to AM1.5 conditions (844 W/m^2), the power generated will be approximately 100 W, and the energy corresponding to the average 5.5 sun hours per day (data taken for the state of Queretaro, Mexico), in agreement with (1) is 550 Wh.

Solar Thermal Plane Collector (STPC) is converting the sun radiation into heat stored in water or air circulating within the collector. Its efficiency η_T is usually 60 – 70 % [4-6], so thermal energy generated by STPC with area A_T during the sun hours will be

$$E_T = \eta_T W A_T \Delta t_1, \qquad (2)$$

and for each square meter of an area, the daily thermal energy produced is around 3 kWh.

Wind Generator (WG) utilizes a secondary product of solar radiation – wind, and its performance is determined, first of all, by the wind velocity v. For a WG "controlling" the area A_A of air flux, the power W_W converted to electricity is the part η_W (WG efficiency) of the corresponding air flux kinetic energy per unit time which is equal to 0.5 $\rho V v^2$, ρ being the air density and V – volume per second of the air flux controlled. For the latter we write $V = A_A v$, and thus obtain

$$W_W = 0.5\, \eta_W \rho A_A v^3, \qquad (3)$$

so the total energy E_W produced during the working time interval Δt_2 will be

$$E_W = 0.5\, \eta_W \rho A_A v^3 \Delta t_2. \qquad (4)$$

Here the corresponding time interval can be 24 hours per day.

Taking the flux controlled area equal again to 1 m^2, air density ρ = 1.29 kg/m^3, wind velocity 8 m/s which is considered as minimum for a good EG performance, and the effectivity 0.25 (some average value), we get from (3) the power 82.6 W; for 24 hours per day performance, according to (4) it gives approximately 2 kWh of energy.

The estimations made show that each of the devices considered produces considerable amount of energy per

IEEE Catalog Number: 04EX865
ISBN: 0-7803-8532-2 ©2004 IEEE

day (from 0.55 to 3 kWh), which could be utilized for domestic or other applications. The analysis below will show the advantages in combining these elements in hybrid systems, and specific demands connected with this combining.

2.2. Thermal-Wind (STPC+WG) Hybrid System

This complex may be useful for thermic applications (for example, to stabilize the temperature regime of the greenhouse or a small living house, when the energy generated during the day by STPC is collected by hot water which is stored in thermally insulated water tank, to be used at night for house heating), with the use of the electricity generated by the WG also for heating (through an electric heater with an efficiency practically 100 %, or in a heat pump system where the efficiency could be practically doubled). The efficiency of the STPC almost linearly decreases with the wind velocity; this decrease ought to be compensated by the effect of wind generator (its power is never linear with the wind velocity, so the compensation will be within some limits; actually, for a strong wing, there could be overcompensation). We can introduce an average wind velocity v_a and find the conditions of energy stabilization in relation to relatively small deviations ($\pm \Delta v$) of this velocity, taking $|\Delta v| < v_a$.

Thus, for the STPC efficiency we write

$$\eta_T = \eta_T^o (1 - \alpha v) = \eta_T^o [1 - \alpha(v_a \pm \alpha\Delta v)],$$

so that

$$E_T = C [1 - \alpha(v_a \pm \alpha\Delta v)], \text{ where } C = WA_T \Delta t_1, \qquad (2A)$$

and for the WG

$$E_W = C^*(v_a \pm \Delta v)^3 \approx C^*(v_a^3 \pm 3v_a^2\Delta v),$$

$$C^* = 0.5\eta_W \rho A_A \Delta t_2.$$

Then for the total energy produced by the system per day we have

$$E_{tot} = [C(1 - \alpha v_a) + C^* v_a^3] \pm (3 C^* v_a^2 - C\alpha) \Delta v \qquad (5)$$

Now we have the condition of stability of the system energy as

$$(3 C^* v_a^2 - C\alpha) = (1.5\eta_W \rho A_A \Delta t_2 v_a^2 - WA_T \alpha \Delta t_1) = 0. \quad (6)$$

We shall see below how this condition could be applied to a real system. However, one general remark could be made now. The wind generators most frequently used (HA, or Horisontal Axis devices) demand very high wind velocity for normal performance (8 m/s and more). At these conditions, the thermal collectors have very low efficiency, and their use is not practical; the supportable wind velocity for their application is 3 – 5 m/s. It means that for the hybrid system of the kind discussed, the HA EG is not a good choice; the Vertical Axis (VA) devices are more efficient at relatively low wind velocities.

*2.3. **Photovoltaic-Thermal (PVM + STPC) System***

This system (so-called "combi-panel") has an evident advantage compared to the separate performance of the devices combined that the STPC absorbs the excessive heat of the PVM thus cooling it and because of that enhances the efficiency of the PVM. It is also clear that the total amount of energy produced per unit area increases. The detailed analysis of thermal balance conditions in this system was published in [7]; here we repeat our main conclusions. All the previous papers on the subject (see, for example, [1-5]) taken for granted that the systems elements have to be of the same area. However, it is evident that the presence of the PV module above the solar collector reduces the heat flux to the collector and thus its efficiency; on the other hand, the collector ability to extract heat from the PVM is reduced while the water (air) inside it is heated. Therefore, the optimal case would be to make PV module of smaller area than that of the heat collector, and to place it above the initial collector's part (i.e. that corresponding to the entrance of the cold water).

Another point is that the conventional PVM usually could not provide a good thermal contact with the STPC, so, this hybrid system demands a special construction of the PVM with a high thermal conductivity of the substrate used; one example of this construction is given in [7].

2.4. Wind-Photovoltaic (WG + PVM) System

These systems are already in use [8,9]; it is the only type among the hybrids discussed which does not put any specific demands to the devices combined. The system generates and stores electric energy day and night; since the WG has more working hours per day than the PVM, low-power WG could match the higher power PVM. To guarantee the normal performance of the system at different conditions of weather, the excessive battery bank ought to be used. This system is most effective in places with very high wind velocity: in addition to the WG driving, the wind stabilizes the PVM temperature and therefore the efficiency of its performance.

2.5. Wind-Thermal-Photovoltaic System

Here we consider the PV/Thermal system discussed at *2.3* in combination with the wind generator WG, the system provides electricity generated by PV module (at daytime) and by the wind generator (day and night), as well as the hot water from the STPC (ought to be stored in the thermally insulated vessel to be used in absence of the illumination by Sun). The total energy (electric + thermal) produced by the system per day will be

$$E_{tot} = (\eta_{PV} A_{PV} + \eta_T A_T)W\Delta t_1 + 0.5\eta_W \rho A_A v^3 \Delta t_2. \qquad (7)$$

The specific demands to the PVM based on the necessity of a good heat exchange between the PVM and the STPC are the same as in *2.3*, and the appropriate climatic conditions for the system operation – same as in *2.2*.

III. EXPERIMENTAL DETAILS

The solar heat collector STPC used in our experiments was of the model Powermat, with water as a heat collecting agent, having the surface area of 4 m^2; approximately 90 % of the surface area is controlled by the internal tube system providing an efficient heat interchange. The black PVC absorber covering the collector is resistant to UV solar radiation (the guaranteed lifetime is 20 years) and provides a small weight of the panel (about 3 kg in empty state, and 5 kg when filled with water). The maximum heating efficiency at the absence of the wind estimated using the Hottel-Whillier model [4] was around 60 – 70 %, which corresponds to the best collectors known. This result is illustrated by Fig. 1 giving the dependence of the efficiency upon the temperature difference between the water entering the collector and the ambient temperature T_a. The dependence is practically linear, in a good agreement with the Hottel-Whillier model, and the maximal value is close to 70 % indicating good performance of the collector. The expression used to find the STPC efficiency from experimental data was

$$\eta_T = M_t C_c (T_o - T_i) / GS \qquad (8)$$

where M_t is the water flux (mass per second), C_c is the water specific heat capacity, T_o is the output water temperature, and T_i - its input temperature.

The PV modules investigated and used were of crystalline Si type (c-Si; in particular, we used the module made by Russian plant OKB “Krasnoe Znamya” OKBKZ M100/12 with an area of about 1 m^2 and the power generated under AM1.5 solar radiation of 100 W, and the other one assembled in our laboratory from the cells 85×85 mm^2 made by the same company). Besides, in the experiments designed to achieve a good thermal contact with the collector, we used the PVM made of amorphous Si (α-Si, ECD Company, Troy, Michigan, USA) and CuInSe$_2$ (CIS) commercial module made by Siemens, USA. The electric efficiency of all the PV modules used was between 10 and 18 %. The prototype panel which we constracted to achieve the best thermal contact (see [7]) was made on Al substrate covered with thin film of PMMA/silica composite dielectric coating, with OKBKZ-made 6 c-Si solar cells 85X85 mm^2 area, and the glass cover.

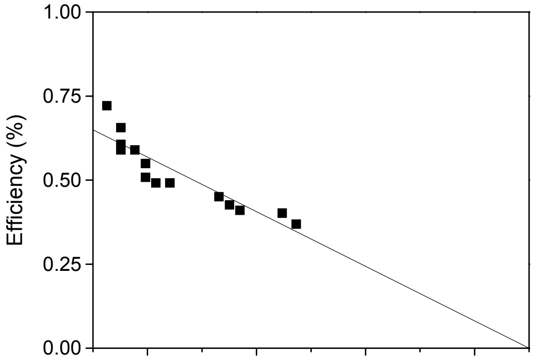


Fig. 1. The thermal efficiency of the STPC studied depending on its temperature.

The wind generator was developed and built in our laboratory (Fig. 2). The vertical axis (VA) model of Savonius type, 3 m high, with the active area A_A = 1.5 m^2, having the automobile alternator with the home made gear-box as generating unit, under conditions of the moderate wind typical for the region of application (state of Querétaro, Mexico, average wind velocity about 5 m/s) it provides in average 40 W of electric energy operating at 120 rpm (see Fig. 3).

The whole system made according to Chapter *2.5* above, is schematically shown in Fig. 4 (the construction scheme – 4.a, electric scheme – 4.b). The electric part of the system includes the battery bank (4 sealed lead-acid batteries “Prism” 12 V, 105 AH each), Solar Charge Controller of the model Steca (Germany) and the DC-AC Inverter Proam.

The arrangement made to investigate the regime of the solar collector included two home-made electrical digital thermometers (1, 2 in Fig. 4.a) based on the temperature sensors LM335, the water flux meter CICASA Delaunet MD-15 (3 in Fig. 4.a), all three devices mentioned were connected to the computerized data acquisition system (4, ibid). The electrical connections scheme (Fig. 4.b) was made according to the generally accepted rules and notations, and does not demand comments.

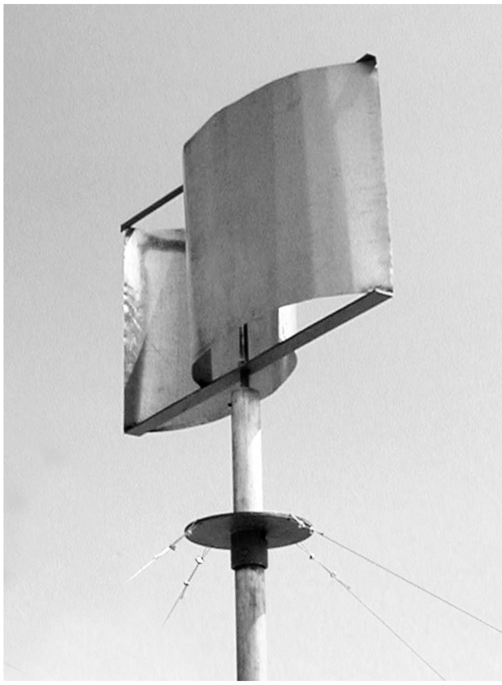


Fig.2. Vertical Axis Wind Generator constructed.

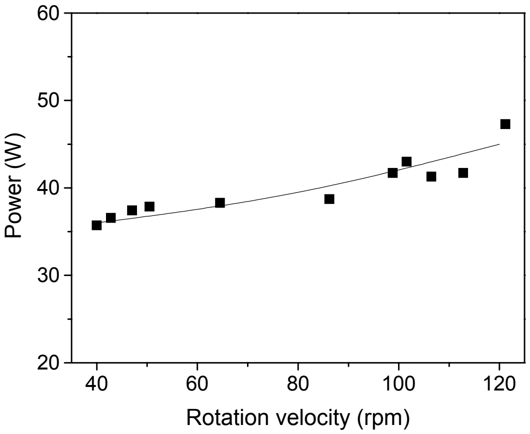
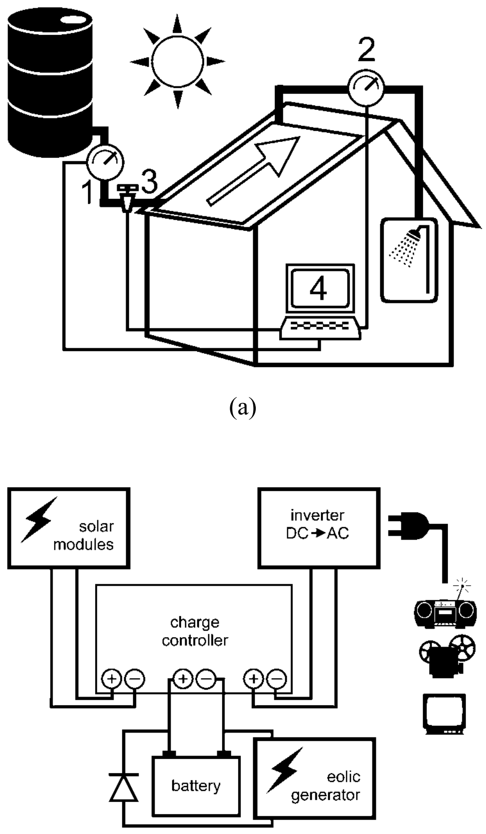


Fig.3. Dependence of power yield of EG on rotation velocity.



(a)

(b)

Fig.4. Structural (a) and electric (b) scheme of the experimental setup.

IV. RESULTS AND DISCUSSION

The devices used for study of hybrid systems performance were capable of production per day at normal working conditions discussed above $E_{PV} = 0.55$ kWh (PVM M100/12) and $E_W = 0.96$ kWh (home made WG) of electric energy, plus $E_T = 12$ kWh of thermal energy (STPC Powermatt; the value given refers to the absence of wind). From (3) we find that our WG generating 40 kW at wind velocity $v_a = 5$ m/s has an efficiency $\eta_W = 0.3$ which could be considered as a good parameter. At this wind velocity, the STPC will produce, according to (2A), 10.1 kWh of thermal energy per day (to find this value, we determined experimentally the coefficient α in (2A), taking measurements of the STPC efficiency depending on v. Thus we obtained $\alpha = 0.032$ s/m).

In *Thermal-Wind Hybrid System* designed for building heating purposes, according to discussion in *2.2*, at average wind velocity of 5 m/s (expression (5)) it will provide approximately 11 – 12 kWh of heat energy, depending on the way of transforming of electric-to-heat energy. To discuss the heat production stability of the System in relation to small variations of wind velocity, we have to calculate the variations in the energy generation by the system's elements according to (6). For the parameters given, we get the first part of (6) describing the dependence of WG productivity upon the changes of v $(1.5\eta_E\, \rho\, A_A\, \Delta t_2\, v_a^2)$ equal to 0.576 kWhs/m, and the second part (similar dependence of the STPC productivity, $-W A_T\, \alpha\, \Delta t_1$) equal to -0.594 kWhs/m. Thus we see that their sum is reasonably close to zero, i.e. our system is well balanced. According to the values found, the daily variations in energy production caused by changes of wind velocity $\Delta v = \pm 3$ m/s will be around 0.05 kWh, which is less than 0.5 % of the total energy.

In *PV/Thermal Hybrid System* discussed in *2.3* above we obtain, in first approximation, the above mentioned amount E_{PV} of electric energy and E_T of thermal energy, with the difference that now the whole energy is provided by the area A_T, not the sum of areas $A_T + A_{PV}$. To get an additional advantage caused by the PVM cooling in thermal contact with the STPC, a special PVM construction is needed; in [7] we have shown that the actual increase of the PVM efficiency could be as high as 10 %.

Our *Wind-Photovoltaic Hybrid System* (2.4 of the above discussion) produces daily approximately 1.5 kWh of electric energy at average conditions of state of Queretaro, Mexico (we should stress that our model of WG is good for moderate wind velocities; for more windy places, the HA models will be better). For actual utilization of this energy with conentional electrical devices, an energy storage, control and conversion appliances are necessary, as shown in Fig. 4 and discussed in Chapter III above.

Finally the *Wind-Thermal-Photovoltaic System* (2.5) provides (at average conditions of the state) around 1.5 kWh of electric energy and 10 kWh of thermal energy. Depending on the necesities and the actual climatic conditions, any part of electric energy produced can be used for stabilization of thermal regime; on the other hand, this amount of energy is sufficient to operate one tele classroom equipped with receptor of educational satellite programs and TV-video set during 6 hours a day, which was proved experimentally in one of the rural schools of the state (the classrom is in a constant use since August 2002).

V. CONCLUSIONS

The main conclusion is that the hybrid systems, as a rule, are not efficiently working when made by mechanical combination of the existing devices. Some of them, if not all, have to be designed and constructed especially for a particular system. Thus, the photovoltaic panel for applications in a PV/Thermal system has to be designed in a way optimal to provide a good thermal exchange with the heat collector, which needs specific materials and arrangements (the ideal would be the panel transparent for part of the solar spectrum which is not absorbed by its semiconductor material, and having a good heat exchange with the collector). Another example is the Wind Generator for Wind/Thermal systems: it has to be designed for relatively low wind velocities, and the vertical axis device can be recommended in this case. The experimental systems designed, built and studied confirm our conclusions.

VI. AKNOWLEDGEMENTS

The authors would like to acknowledge the support of CONACYT of Mexico, through the project 33901-U.

VII. REFERENCES

[1] E. C. Kern Jr. and M.C. Russel, “Combined photovoltaic and thermal hybrid collector systems”, *in Proceedings 13th ISES Photovoltaic Specialists*, Washington D.C., USA, 1978, pp. 1153-1157.

[2] P. Raghuraman, “Analytical predictions of liquid and air photovoltaic/thermal flat plate collector performance”, *J. Solar Energy Engineering*, vol. 103, 1981, pp. 291-298.

[3] A.K. Bharava, H.P. Garg and R.K. Agrawal R.K., “Study of a hybrid solar system – solar air heater combined with solar cells”, *Energy Convers. Mgmt.*, vol. 31, 1991, pp. 471-479.

[4] L.W. Florschuetz, “Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plale collectors”, *Solar Energy*, vol. 22, 1979, pp. 361-36

[5] H.P. Thomas, S.I. Hayter, R.L. Martin and L.K. Pierce, “PV and PV/Hybrid products for buildings”, *in Proceedings of 16th European PV Solar Energy Conf.,* Glasgow, U.K., Vol. II, 2000, pp.1894-1897.

[6] H.A. Zondag, D.W. De Vries, W.G. Van Helden et al., “The thermal and electrical yield of a PV/Thermal collector”, *Solar Energy*, vol. 72, 2002, pp. 113-128.

[7] R. Zakharchenko, L. Licea-Jimenez, S.S. Perez-Garcia et al., “PhotovoltaicSolar Panel for a Hybrid PV/Thermal System”, *Sol. En. Mat. Sol. Cells*, vol. 82, 2004, pp. 253-261.

[8] R. Flores and J. Agredano, “Battery Monitoring in Mexican Hybrid Power Systems”, *in Workshop Photovoltaic-Wind Hybrid Systems for Remote Power Supply*, Mexico, 1997, pp. 172-183.

[9] S. Lopez Rios, “Planta Eléctrica Híbrida San Juanico”, *in Mexico Renewable Energy Program Review Meeting*, Cuernavaca, Mexico, 2000, pp. 18-19.