Design of a Roof-Top Solar-Wind Hybrid System With a Solar Still for an Urban Residential Building in Delhi

Krishan Kant Sharma*, Manu Sharma, D.S. Bilgi*****

Abstract

This paper presents a design of a hybrid system consisting of, a photovoltaic module, an aero generator and a solar still, to be mounted at the roof of a tall residential building in a suburban location near Delhi. The design incorporates an innovative arrangement to distill water and thus utilize a significant part of energy which gets dissipated in the form of heat in a conventional system. Based on the available weather data and typical geometry of the building, the ratings of the various components of the system are worked out. In the proposed system, a photovoltaic module feeds the load comprising the critical electrical load (CEA) of the household, a storage battery bank and a drinking water distillation tank at the rooftop. The wind driven dc generator also feeds this load. The energy outputs of the PV module and the wind generator, both vary with time over the day and the climatic conditions. There are periods of time when the generated power exceeds the load of CEA. During such periods the surplus energy will be stored in the battery bank. When the batteries get fully charged up, the surplus power will go to the solar still and augment distillation of water. Thus the solar still will utilize the surplus energy and also collect solar radiation directly for distillation of drinking water. The objective is to utilize the available wind energy and solar energy at the given roof-area, effectively. The performance of the system under different seasonal conditions is predicted by computer simulation.

Key Words: Hybrid system, SPV Module, Solar Still

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1. Introduction

Electrical energy and drinking water are basic needs of human life. Yet in most areas of the world these are in short and erratic supply. Even in some elegant looking well furnished buildings in the suburban areas of metropolitan cities such as Delhi, people are facing problems of frequent power cuts and perennial shortage of safe drinking water. Whereas breakdowns of electricity lead to acute discomfort and disruption of normal life, lack of adequate and safe drinking water is the root cause of many health-related problems. In summers these difficulties are much more pronounced.

It has been reported [1] that 80% of all diseases in developing countries are related to inadequate and unsafe drinking water. The biological requirements of human body for water have been studied [2] and the adverse effects of dehydration have been reported [3]. The recommended value of domestic drinking water in hot climatic regions such as Delhi, is 4.5 L/day for each person [4]. It should be safe as well as acceptable in appearance, taste and odour. It should not be contaminated with biological or chemical substances beyond their threshold values [5].

Most of the conventional water treatment techniques are energy intensive and get badly affected during the power cuts. A viable solution to this problem lies in utilizing a suitable combination of solar energy and wind energy which are clean, abundant, ever- lasting, and easily available; with a solar still.

As a case study, the present paper considers, a high-rise sub-urban residential building that faces problems of frequent power cuts coupled with inadequate and unsafe drinking water. The estimated daily average electrical demand of the household is 20 kWh out of which 4 kWh is required to meet the critical electrical load (CEA). Here it is assumed that the critical load consists of two lights, two fans and one plug point that will be connected to the proposed hybrid system to keep it running even during the utility power-cuts. Analogous to the essential electrical appliances, a minimum supply of safe drinking water is absolutely necessary. In the present study, it is assumed that at least 50 liters of drinking water per day (LPD) must be made available to the residence even while the utility water supply is shut down. For this purpose, a roof-top solar still will be installed that will distill water taken from a source such as a tube-well or a rain water storage tank. The surplus energy converted by the SPV module and the wind-generator will be used for distillation of drinking water. Figure 1(a and b) shows the schematic block diagram of the system.

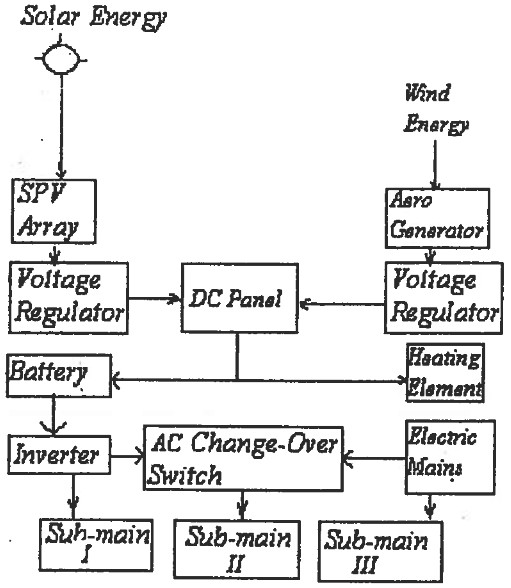

Fig.1(a): Block diagram of the proposed electrical supply to a suburban household

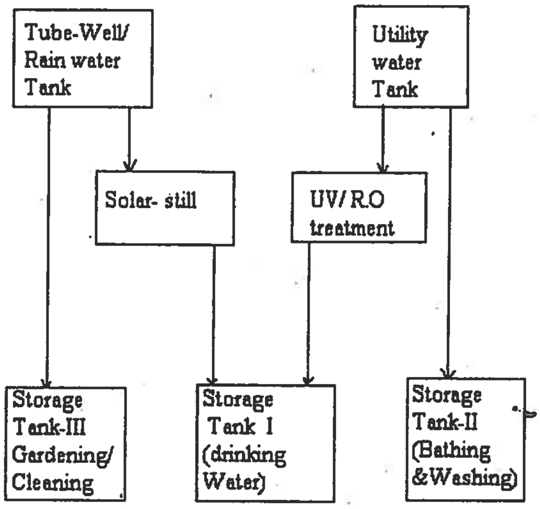

Fig.1(b): Block diagram of the proposed water supply to a suburban household.

The hybrid system will consist of the following main components:

- A solar photovoltaic (SPV) module with a storage battery
- A wind energy driven turbine-dc generator (WG) with a storage battery
- A solar still that will collect solar radiation for water distillation and also

utilize the surplus power generated from the SPV and the wind generator (WG). -

An electric control panel that will monitor the generation and consumption of energy between the critical domestic electrical load and the water distillation device.

A brief description of these components is as follows:

1.1 Solar Distillation

The thermal energy present in solar radiation has been successfully employed to remove dissolved and suspended particles from water by the processes of evaporation and condensation. It has been claimed [6] that solar distillation effectively eliminates all water borne pathogens, salts and heavy metals. Various types of solar distillation devices (solar stills) are being used all over the world. Solar stills, as small as 0.9m×1.5m in area have been reported to produce 14 l / day in summer and 7 l /day in winter [7].

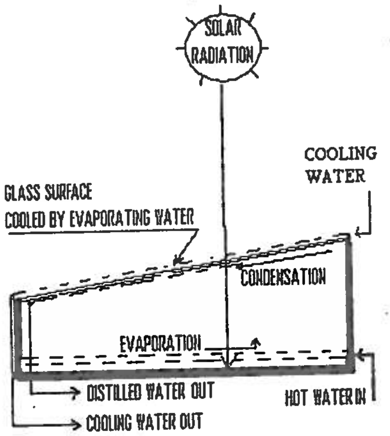

Fig.2 : The proposed solar still using a cooling arrangement for the condensing surface and an incoming hot-water supply to increase the per unit area yield

A solar still usually consists of a shallow tank of water covered with a transparent glass, (Fig.2). The water in the tank receives solar radiation transmitted through the glass and evaporates. The water vapor condenses at the lower surface of the glass cover, from where it is collected in a distilled-water tank. In the present study we propose two additional features: An arrangement for providing a layer of cooling water at top of the glass cover, and another arrangement to supply hot water at the bottom of the solar still. The aim is to enhance the rates of evaporation and condensation and hence the yield of the solar still per unit of area.

1.2 Availability of Solar Radiation

The amount of solar energy reaching a surface on earth depends on the position of sun, the climatic conditions of the sky, the time of the year and the orientation of the surface. It may be determined using the well known geometrical and empirical relations e.g. [8] as follows:

$$\mathrm{Sin}\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \quad \text{........(1)}$$

$$\sin\alpha = \cos\delta \sin H / \cos\beta \quad \text{........(2)}$$

$$I_{DN} = Ae^{-B\sec\beta} \quad \text{........ (3)}$$

where

I_{DN} is the Intensity of solar beam radiation on a surface kept normal to solar rays, A is the apparent solar irradiation at air mass zero and it varies with time of the year, B is atmospheric extinction coefficient, β is solar altitude angle, α is solar azimuth angle, L is local latitude, δ is declination and H is the hour angle. The values of the solar angles and intensity of solar radiation can also be computed using a computer software such as Trnsys [9]. For the purpose of the present case study, weather data have been taken from a handbook [10] and the other results have been computed using [9]. Fig. 3 depicts the mean hourly values of solar intensity on a horizontal surface for different months in Delhi (latitude 28.5°). In table1, the mean daily values of solar energy/m^2 received on the horizontal surface are given.

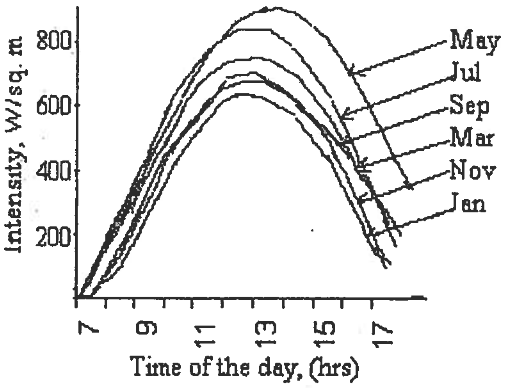

Fig. 3: Mean hourly values of solar intensity on a horizontal surface in different months in Delhi, latitude of 28.5°

Table 1: Mean daily solar energy received on a horizontal surface for different months in Delhi (latitude angle 28.5°)

Month	Energy Received (kWh/m^2)
January	3.95
March	6.10
May	7.24
July	5.37
September	5.55
November	4.48

1.3 Utilizing Solar UV Radiation in a Solar Still

Ultra violet (UV) radiation is effective against all waterborne pathogens including viruses. The inactivation credits of UV irradiation for different species of viruses, bacteria, and protozoa have been studied by several scientists and quantitative results have also been reported [11]. However, the microorganisms embedded in particles or in bio-films can escape from the UV irradiation.

About 3.5 % of solar energy reaching the surface of earth is in the form of UV radiation. It can be utilized for treating water. However the intensity of the radiation gets exponentially diminished (attenuated) as it transmitted through the water:

$$I(d) = I_0.\exp(-k.d) \quad ......(4)$$

where I(d) is the value of intensity of the radiation at a distance d along the path of transmission, I_0 (is the value of I at d = 0 and k is the coefficient of attenuation. The value of k depends on the nature of medium (water particles) as well as the nature and concentration of the dissolved particles and the suspended particles. The value of k is generally determined experimentally for the given set of conditions. In the present study, we assume k = 25 (a typical value for ground water), so that the intensity of transmitted radiation will be reduced to less than 10 % when it covers a path of 0.1m through the medium (water). Following this reasoning, the required depth of water in the solar still will be at least 0.1 m for making nearly full (> 90%) use of the available solar UV radiation.

1.4 Utilizing Solar Photovoltaic Energy

Solar radiation is directly converted into electrical energy in a device called a solar cell that is usually a p-n junction diode made of suitably doped silicon material. Various device configurations employing single crystal, poly-crystal, amorphous and thin film structures have been developed [12]

The conversion efficiency of a solar cell depends on the intensity and wavelength range of incident radiation, the temperature of the cell and the band gap of the p-n junction. In the present study, we propose a method for providing a cooling arrangement for lowering the operating temperature of the solar cell. Fig. 4 is a schematic showing the solar photovoltaic module (SPV) with a heat exchanger. The cooling water will extract heat energy from the bottom of the SPV and the hot water will be supplied to the solar still. This will improve the performance of both the SPV as well as the solar still.

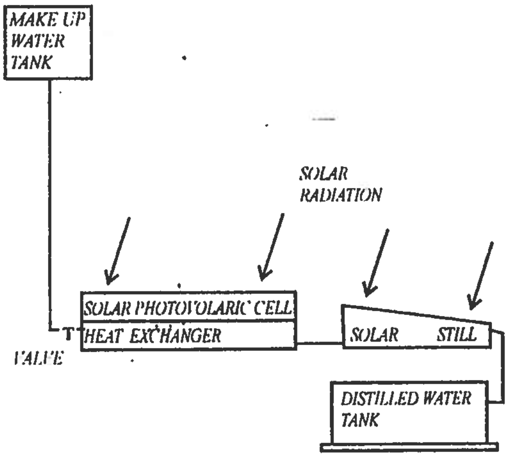

Fig. 4: A combination of solar photovoltaic module with heat exchanger and a solar still

When a solar cell connected to a load resistance R_L is exposed to solar radiation, a current I_L flows through R_L and a voltage V is developed across it as shown in Fig. 5. The current-voltage relationship for the device may be written as

$$I_L = I_P - I_s(e^{qV/kT} - 1) \quad ......(5)$$

where I_P is the photo current caused by the excess charge carriers generated by the incident solar energy, I_s is the reverse saturation current of the p-n junction, q is the electronic charge, k is Boltzmann constant and T is temperature in Deg. Kelvine. Under short circuit condition, (R_L=0,V=0), I_L=I_P= Isc is the maximum value of the current that flows through the cell. Similarly, under open circuit condition (R_L =∞, I_L =0), one gets V_{oc} that is the maximum value of the voltage developed I_L decreases with increase in voltage as shown in the VI characteristics of the photovoltaic cell (Fig.6). The values of I_{sc} and V_{oc} depend on the intensity of the incident solar radiation and temperature. Fig.6 also depicts the effect of temperature clearly. It has been found that [12] that the efficiency of a silicon solar cell decreases linearly with temperature in the range 20 °C to 200 °C. Thus if the efficiency of the cell is 15% at 20°C, it will get reduced to 9% at 60°C and to 2.5% at 200°C.

On the VI characteristic of a solar cell there exists a point M that gives the maximum value of the product of the voltage and current (P_{MAX}). Obviously, one would like to operate the cell at or very close to the point P_{MAX} in order to get the optimal utilization of the incident solar energy. In the present study we propose a method to regulate the operating voltage of the cell by automatically adjusting the load current for optimizing the power output at a given value of solar insolation.

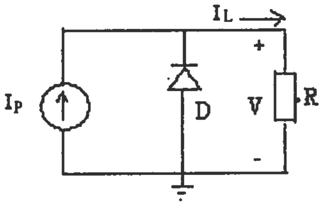

Fig.5: The Equivalent Circuit of a Photovoltaic Cell

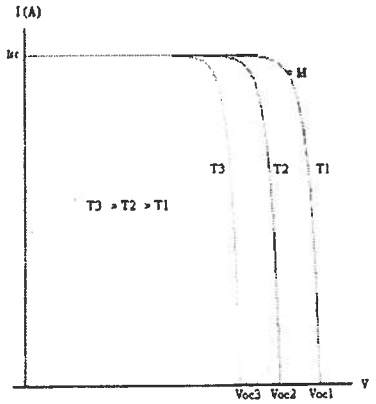

Fig.6 : V-I characteristics of a typical solar cell, showing the maximum power extraction point and the effect of increase in temperature. The V_{oc} and power output from the cell decrease with increase in temperature.

1.5 Evaporative Cooling of the water for Heat-Exchanger

A portion of the out coming water from the heat exchanger will be supplied to the top of the glass cover (Fig. 2) of the solar still where it will flow on the upper surface and evaporate by direct contact with the atmospheric air. The water cooled by evaporation will go back to the heat exchanger. The evaporation process will also keep the condensing surface of the solar still cool and thus increase the distilled water yield.

1.6 Utilizing Wind Energy

The kinetic energy of wind can be harnessed by means of wind-turbine driven electric generator. The conversion of the mechanical energy of wind in to electrical energy is governed by the principles of aerodynamics of the turbine as well as the prevailing atmospheric conditions such as local wind velocity, its direction, the nature of obstructions in the passage of wind, air density etc. Intermittency and unreliability of wind energy are its major draw- backs. There are various types of wind turbines including the horizontal axis turbines and vertical axis turbines. The working principals and structural details of some wind turbines are well described in [8,13]. The instantaneous value of wind power ρ in terms of instantaneous velocity v and air density may be expressed as

$$p = \eta A(\rho v)(1/2\, v^2) \ldots\ldots\ldots\ldots (6)$$

Where η is the efficiency of conversion and A is the area of cross section kept normal to the velocity of the wind. In geographical regions such as Delhi the wind speed is usually small, ranging from 1-6 m/s [14]. Besides, the urban area is riddled by dominating obstructions in the paths of wind. The inadequacy of wind velocity and presence of obstructions invariably make it difficult to utilize wind energy. However, attempts are being made to develop small wind generators suitable for urban locations, including roof-tops of buildings [14,15]. Some encouraging results have been reported relating to harnessing urban cavities, vortices as well as amplification of wind velocity through channeling effect.

The maximum efficiency of a wind turbine was found by a German scientist, Albertz Betz, a scientist who as early as in 1919, stated that the theoretical maximum efficiency of a wind energy converter is 59.5 %. Its practical value is much lower, depending on the inevitable losses associated with the turbine, motor, electrical generator etc. The power extracted by a typical wind generator is approximately

$$P = 0.2\, V^3/m^2 \ldots \qquad (7)$$

where V is the local wind speed taken from the weather data compiled by authors such as [10]. The mean values of wind energy that can be extracted per day per square meter area of turbine (exposed normally to wind), for different months in Delhi are shown in Table 2.

Table 2: Mean daily wind energy received per square meter swept area of turbine for different months in Delhi

Month	Energy Received (Wh/m^2)
January	93.8
March	188
May	220
July	163
September	77.5
November	62.9

2. Sizing the Equipment

2.1 SPV Module

Having assessed the load on the solar photovoltaic system, and availability of solar energy, one can select the equipment to meet the requirements. The rated output of a typical [16] 1.2m long 0.6 m wide module at Standard Test Conditions of 100 mw/cm^2, solar insolation (AM 1.5) and at 25^{0}C Cell- temperature is 70W. This represents about 11% conversion efficiency. In the present study we assume 20% losses (utilization factor = 0.8), due to higher operating temperature, dirt and aging. We have, however, taken into account the effect of cooling water in the proposed heat exchanger and also assumed that the SPV will be operated close to its maximum-power point (16.2V) Based on these parameters and assumptions the average conversion efficiency will be 0.088) and thus the output from 20 solar modules with a total covered area of about 14.4 sq. meters has been computed for different months.

2.2 Sizing the Solar Still

Since we propose to utilize the waste heat from the SPV system, the size of the solar collector of the still will be much smaller than what would be required without the waste heat recovery. Assume that 60% of the heat received by the SPV will be recovered through the heat exchanger, the area of the still to be exposed to the solar radiations directly to meet the requirement of 50l water in the winter months of December-January, may be calculated as follows:

Let the area of the solar still = A

Average daily amount of energy received directly = 4A. kWh/ day .... (8)

Amount of energy received through the heat exchanger = 40 (0.6) = 24 kWh/ day... (9)

Total energy input = 4A + 24 kWh/day ... (10)

Amount of energy required to yield 50 l water/day = 50 (2.5 MJ/3.6)/η = 34.7/ η kWh/day.. (11)

(where η is the efficiency of distillation assumed to be 60% in this case)

Equating (7) and (8), we get A = 8.5 m^2 (12)

So, we take the overall area of the solar still = 10 m^2

The yield of water will depend on the rates of evaporation and condensation in the solar still. Here we assume that the surface of the glass cover will be cooled by a layer of evaporatively cooled water flowing over the glass cover and its temperature will be close to the wet-bulb temperature of ambient air. We also assume that the temperature of water coming into the solar still from the heat exchanger will be maintained at 35 °C by controlling its flow rate and the average rate of mass transfer will be 0.0025 g/ m^2 (equivalent to convective heat transfer coefficient of 6W/Km^2 for the annular space) per kg/kg difference of humidity ratio). The average daily water-yield calculated on these simplified assumptions will be

Daily water yield for January=(0.0025 g/ m^2) (8.5m^2)(24×3600 s)(.029 kg/kg)=53 liters.. (13)

For the remaining months, the water yields will be higher because of the higher values of solar insolation.

2.3 Sizing the Wind Generator

Equation (6) gives the power of a wind turbine-generator set, per unit swept area of the turbine (area of cross section normal to wind velocity), for a given value of wind speed. Using this equation we have computed (Table 2) the mean values of electrical energy per unit swept area of the turbine for different months in Delhi, using the data taken from the handbook [10]. Based on these considerations, we take the swept area of 10 m^2 (radius of turbine rotor =1.76m) which will produce about 2 kWh energy per day in summer and 1 kWh in winter.

3. Results and Discussion

The sizes of the various components of the proposed system have been calculated on the basis of the design electrical load, drinking water requirement, weather data and the climatic conditions in and around Delhi. The estimated daily out puts of electrical energy and distilled water yields, for normal sunshine days, for various months are shown in table 3. During the rainy and cloudy days, solar energy is not available. So, the energy stored in the battery and distilled water stored in the drinking water tank will be used. The proposed capacities of these storage devices will be sufficient for ~~at~~ least 12 hours in absence of any sunshine.

Table 3: Estimated daily electrical energy out put and distilled water yield of the proposed system for different months in Delhi

Month	Estimated daily electrical energy out put (kWh/day)	Distilled water yield (Liters per day)
January	6.46	53
March	8.65	68
May	10.10	88
July	7.50	60
September	7.71	63
November	7.52	62

Another advantage of using the system will be in the form of reduced heat flux through the roof of the building. In summer, 8-10 kWh/day of solar energy will be converted to electricity. This represents reduction in solar heat received by the roof of the building and corresponding reduction in cooling load of the building. During winter, the presence of the solar still and the photovoltaic module, covering about 25 square meters of the roof area will prevent it from direct exposure to the cold ambient air and open sky, thereby reducing heat loss from the building (if it is kept warm inside by air-conditioning etc.).

4. Conclusions

A method for estimation of solar energy requirement of a residential building in a sub-urban area, has been presented. The proposed system is capable of keeping the critical electrical load and drinking water supply running during the utility power-cuts and shortage/disruption of safe drinking water. It can also provide about 50 % back ups for both of these essential amenities. However there is a need to incorporate another source of energy such as roof-top wind turbine, which will run while the sun is not shining.

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