A hybrid wind and hydroelectric power production system in Plaka, Alexandroupolis, Greece

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D.V. Bandekas
International Hellenic University

N. Vordos
International Hellenic University

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J. G. Fantidis
Dept. of Electrical Engineering
Kavala Institute of Technology
Kavala, Greece
Fantidis@yahoo.gr

V. C. Mantzari
Department of Civil Engineering
National Technical University of Athens
Athens, Greece

E. Kalkani
Department of Civil Engineering
National Technical University of Athens
Athens, Greece

D. V. Bandekas
Dept. of Electrical Engineering
Kavala Institute of Technology
Kavala, Greece

N. Vordos
Dept. of Electrical Engineering
Kavala Institute of Technology
Kavala, Greece

Abstract—**The primary objective of this study is to determine a hybrid system, which combines wind and hydraulic energy, able to supply the necessary electrical load of a typical community in a remote location in Plaka, Alexandroupolis, Greece. This is the first effort for utilization of wind and hydraulic energy potential of the aforementioned area. The obtained results prove that the development of a hybrid energy system is feasible, which uses a combination of renewable energy sources in this area, with satisfactory efficiency and without creating environmental pollution.**

Keywords- Hybrid system; Wind/Hydro system; Renewable energy; Evros prefecture

I. INTRODUCTION

Electric energy is essential to everyone's life, an important requirement for financial and social development. The world energy consumption is expected to grow about 57% in the next two decades [1]. Moreover, the electricity demand from emerging economic regions such as China and India is increasing even faster. For these reasons the energy problem in conjunction with the environmental problem continues to be a major topic in the energy and environmental worldwide policies.

The energy crisis and the environmental problems, such as the greenhouse effect, the acid rain and the ozone layer debilitation, are effects of use of non renewable energy sources. The man and the ecosystems are the receivers of the environmental encumbrances. Consequently, it is obvious that the utilization of the solar, wind, hydraulic, biomass and geothermal energy sources is necessary, which are environmentally friendly and are called renewable energy sources. The combination of the aforementioned energy sources has as a result the development of Hybrid Energy Production Systems. Hybrid renewable energy systems, is one of the most promising applications of renewable energy technologies in remote areas, where the cost of grid extension is too expensive and the price of fossil fuels increase radically with the remoteness of location [2-5].

Wind energy is a full-grown electricity production technology constituting an economically attractive solution for the continuously increasing energy demand. However, the wind power production has a well known drawback, is their unpredictable nature and dependence on weather and climatic changes. Energy storage solution is necessary and in this way the hydraulic energy seems to be the better solution [6-9]. At the present time pumped hydro storage systems are considered by engineers to be an attractive alternative for the expansion of power systems [10], as a considerable amount of energy can be stored with this technique and the generating equipment is highly reliable [11]. The stored hydraulic energy can then be retransformed to electricity by operating a hydraulic turbine and then the power output can be extensively regulated. In this work a hybrid wind-hydro system is used in order to supply electricity in a small village. The energy produced by the wind turbine will be transformed to hydraulic energy by a pumping station and stored to an elevated water reservoir.

II. THE EXAMINED CASE

The overwhelming majority of the articles study the small or larger remote Greek islands [12]; however, the present article is the first, which refers in the East Thrace (the most distant main land area in Greece). The area has one of the lowest standards of living in Greece. The Evros Prefecture is the northernmost of the prefectures of Greece. It is located in the eastern and northeastern part of the region of Thrace, and borders Turkey at the Evros river. Evros borders Bulgaria to the north and the northwest. The Rhodope prefecture borders it to the west. At the Rhodope sierra there is an Agia Paraskevi stream. Evros geographical location makes it a natural bridge between the energy-rich Middle East and Central Asian regions. Alexandroupoli is the capital of the Evros Prefecture in Thrace.

The geographical fragmentation of the Evros its separation from the major centre of energy production and consumption. At the height of 300 m there is a village with name Plaka(latitude 40°53 N, longitude 25°43 E) (Fig. 1 from the Google maps). The village has abundant renewable energy sources at hand, principally the wind and the water. The wind resources in particular are especially high, both in terms of intensity and constancy.

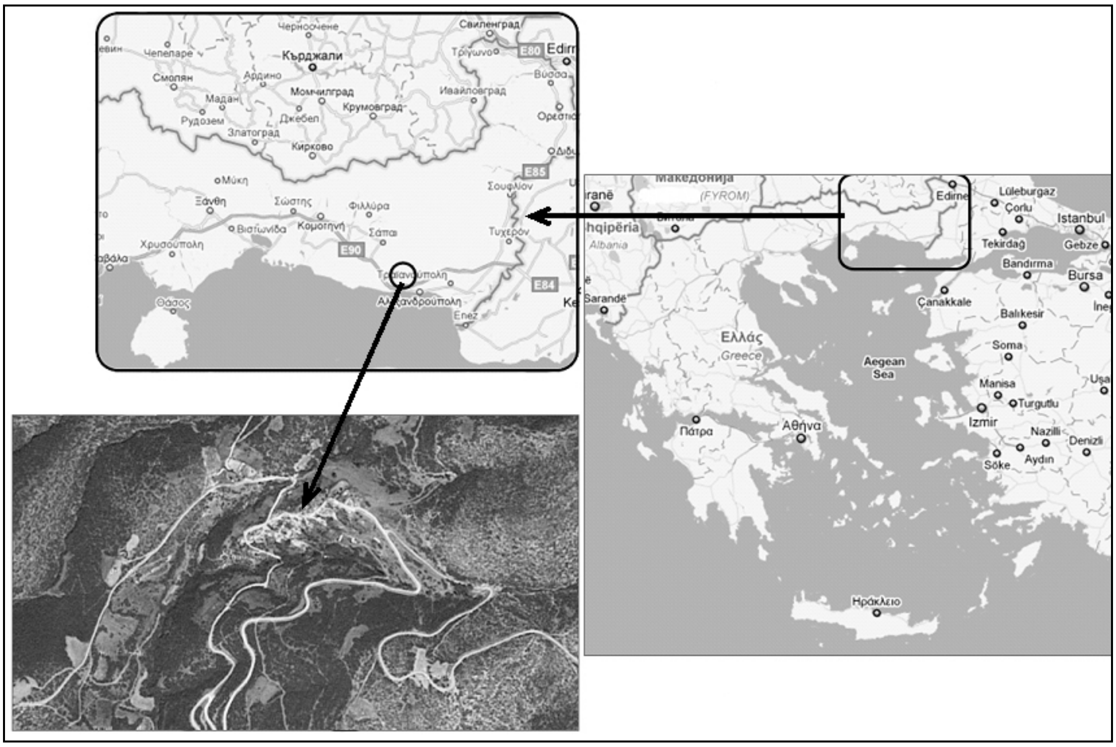

Figure 1. Geographical location of the Plaka village

Pumped storage is viewed today as the most suitable storage technology. A pumped-storage hydroelectric power plant has two (or more) reservoirs at different elevations. At the height of 450 m there is a bridge where is possible to construct a small dam in order to hold the water (upper reservoir). The lower reservoir, with dimensions 40 x 12 x 10 m^3 will construct at the roots of a mountain, near to the village. In this area the terrain is hilly and there is a significant difference in the elevation between the Agia Paraskevi stream and the Plaka village (about 150 m). The power from the wind generator is used to pump water from the lower reservoir into the upper one. In order to produce electricity the potential energy stored in the upper reservoir is released. Water is let out of the upper reservoir(s) in a controlled manner, passing through penstocks and turbines to generate electricity.

The performance of a hybrid Wind–PV system is strongly dependent on the climatic conditions and accurate weather data in a targeted location is essential. The CRES is a source for these data. CRES (Centre for Renewable Energy Sources and Saving) is the Greek national entity for the promotion of renewable energy sources, rational use of energy and energy conservation. The monthly variation of the 3 hourly wind speeds measured at a height of 10 m at Plaka from 1951 to 2001 is shown in Fig. 2. The average annual wind speed of Plaka at 10 m above ground level was estimated at 6.5 m/s [13]. To transfer the wind data acquired to other desired heights, the logarithmic profile equation was used [14].

$$\frac{V(z)}{V(z_r)} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \qquad (1)$$

where V(z) is the wind desired for a height z, $V(z_r)$ is the wind speed reference at the height z_r, and z_0 is the parameter known as the surface roughness height. Fig. 3 shows the probability of wind (at 44 m height) as a function of wind speed.

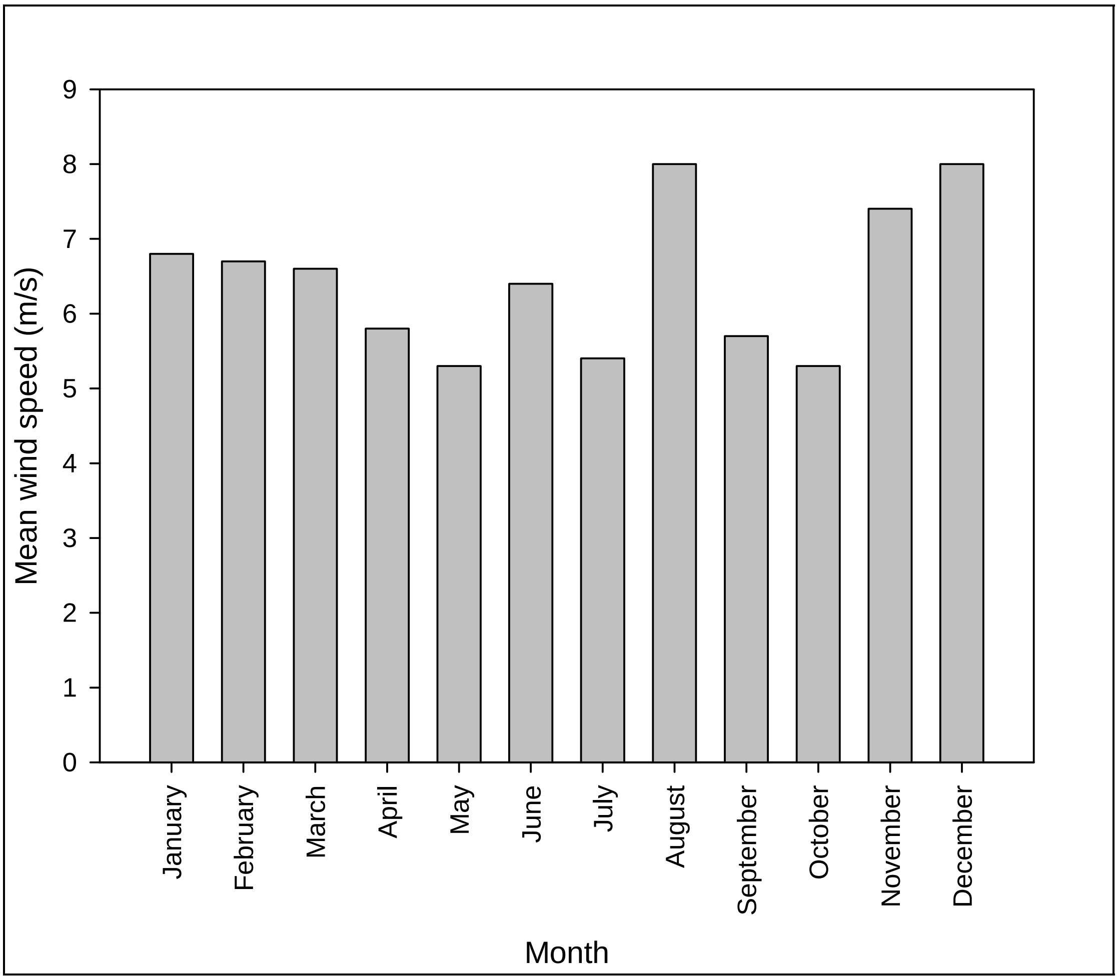

Figure 2. Monthly mean wind speed for Plaka (1951–2001)

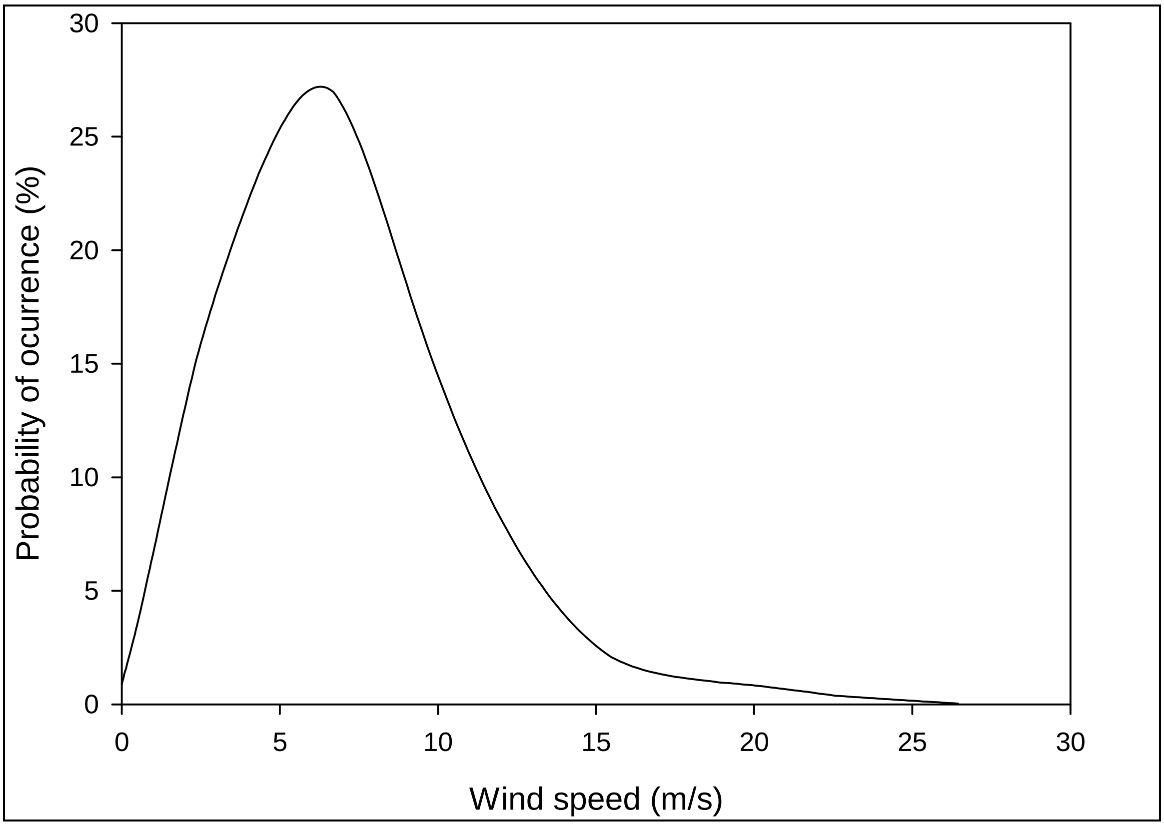

Figure 3. Wind frequency distribution for Plaka (at 44 m height)

A. Wind turbine performance model

Choosing a suitable wind turbine model is very important for the power simulations. For a typical wind turbine, the power output characteristic can be assumed in such a way that it starts generating at the cut-in wind speed V_C, the power output increases linearly as the wind speed increases from $_{VC}$ to the rated wind speed V_R. The rated power P_R is produced when the wind speed varies from V_R to the cut-out wind speed V_F at which the wind turbine will be shut down for safety considerations. Then the wind turbine power output can be simulated by [15].

$$P_{WT} = \begin{cases} P_R \dfrac{V - V_C}{V_R - V_C} & (V_C \le V \le V_R) \\ P_R & (V_R \le V \le V_F) \\ 0 & (V < V_C \ or\, V > V_F) \end{cases} \qquad (2)$$

With intention to estimate the wind energy output in this paper we selected an E33 model from Enercon Corporation. The technical characteristics of the wind turbine used in the studied project are listed in Table 1. The power output curve of the Enercon E33 - 330kW turbine is shown in Fig. 4. The power coefficient curve as a function of wind speed is also plotted in Fig. 4 [16]. The average values of the wind speed for a period of one year using annual time records with a 3 h resolution calculated and the calculated power output at the Plaka location are depicted in Fig. 5. The amount of the wind energy transformed and stored as hydraulic energy.

TABLE I. SPECIFICATIONS OF THE WIND TURBINE

Rated power (kW)	**Cut-in speed VC (m/s)**	**Rotational speed (rpm)**	**Cut-off speed VF (m/s)**	**Hub height (m)**	**Blades**	**Swept area (m^2)**	**Rotor diameter (m)**
330	3	18-45	28-34	44	3	876	33.4

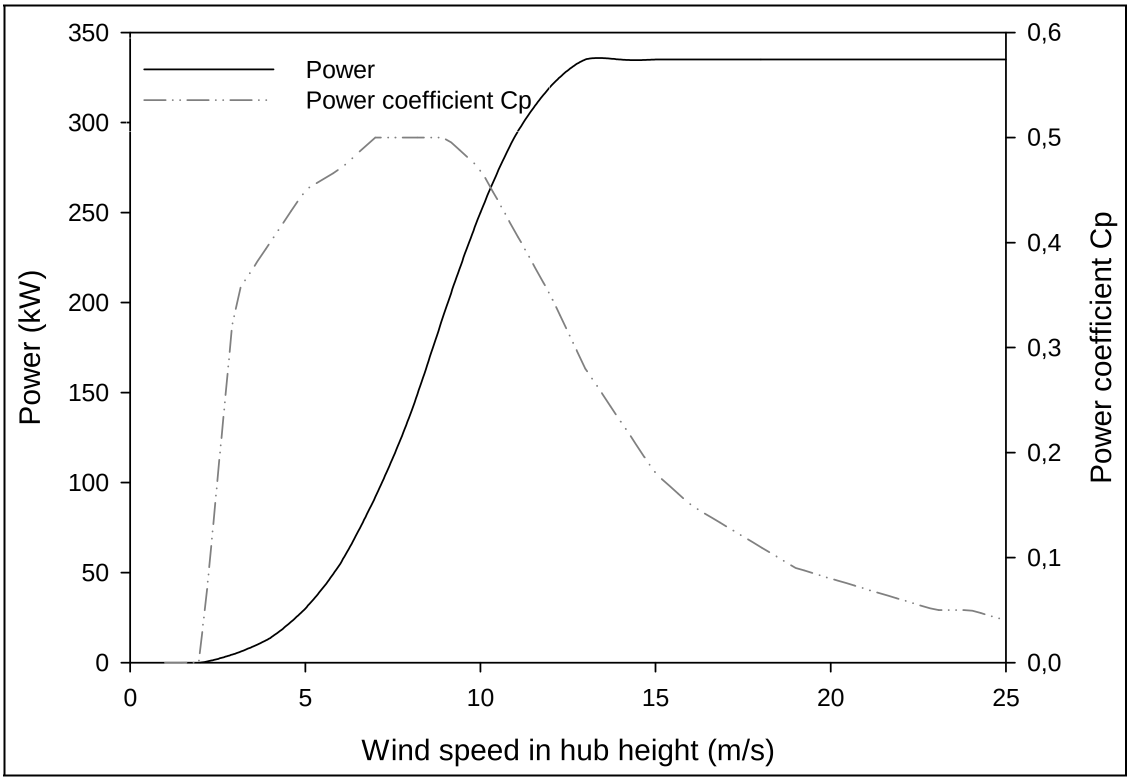

Figure 4. Wind energy and power coefficient curves capacity factor relatives to the wind speed

B. Hydro station model

For each pump and turbine unit, the corresponding efficiency curve is taken into account. For a given electrical power, the required water flow rate is calculated using the following equations (3-8), for pump and turbines units:

$$P_{pump}=\rho\cdot g\cdot Q\cdot(H+h_f)/(1000\cdot n_{pump}\cdot n_{el}) \qquad (3)$$

$$P_{turbine}=\rho\cdot g\cdot Q\cdot(H-h_f)\cdot n_{turbine}\cdot n_{el}/1000 \qquad (4)$$

where: P_{pump} is the power consumed by the pump (kW), $P_{turbine}$ is the power produced by the turbine (kW), ρ is the water density (for clean water it is 1000kg/m^3), g is local gravity acceleration (9.81m/s^2), Q is the water flow rate (m^3/s), H is the head of the hydroelectric generating unit (m), $h_f = k\cdot Q^2$ is the head loss in pipes (m), n_{pump} is the water pump's efficiency (%), n_{el} is the electrical efficiency of pumps (%) [17].

For the estimation of the head loss various methods are proposed in the bibliography. Gordon and Penman [18, 19] provide a simple equation for determining steel penstock diameter of small hydropower installations:

$$D = 0.72\cdot Q^{0.5} \qquad (5)$$

where: D is the penstock diameter (m).

Then, the head loss is given by the Darcy-Weisbach formula as:

$$h_f = f\frac{L\cdot V^2}{D\cdot 2g} \qquad (6)$$

where: f is a numerical friction factor, L is the length of pipe (m), V is the velocity of flow in pipe (m/sec). In a practical initial approach, f = 0.02 can be set in the Darcy-Weisbach equation to get an estimate of head loss [18]. Velocity of flow in the pipes can be estimated by the equation:

$$Q = V\cdot\pi\cdot\frac{D^2}{4} \qquad (7)$$

Equations (4), (5) provide an estimation of head loss, h_f, as a function of the square of the water flow rate:

$$h_f = \frac{f \cdot L}{D^5 \cdot 2g \cdot \left(\frac{\pi}{4}\right)^2} \qquad (8)$$

Equation (8) has been incorporated in (3), (4) for the hydro-power calculation.

In our project the H is equal to 150 m and L = 2000 m. A pump storage unit absorbs the entire energy from the wind turbine. The quantity of water which elevates from the lower reservoir to the upper reservoir every 3 h is shown in Fig. 6. The total water quantity which transferred from the lower level reservoir to the upper level one calculated equal to 3142734 m^3 (SV_a).

With intention to calculate more precisely the water quantity, is calculated the evaporation and the rainfall for each month over the period from 1951 to 1997 (Fig. 7). Plaka receives more winter rainfall than autumn. Evaporation is the reverse of rainfall and rises as temperatures increase. In Greece the climate is characterized by hot and dry summers so the evaporation in June to August is more than twice the evaporation of November to April. We computed water evaporation by the Penman-Monteith equation.

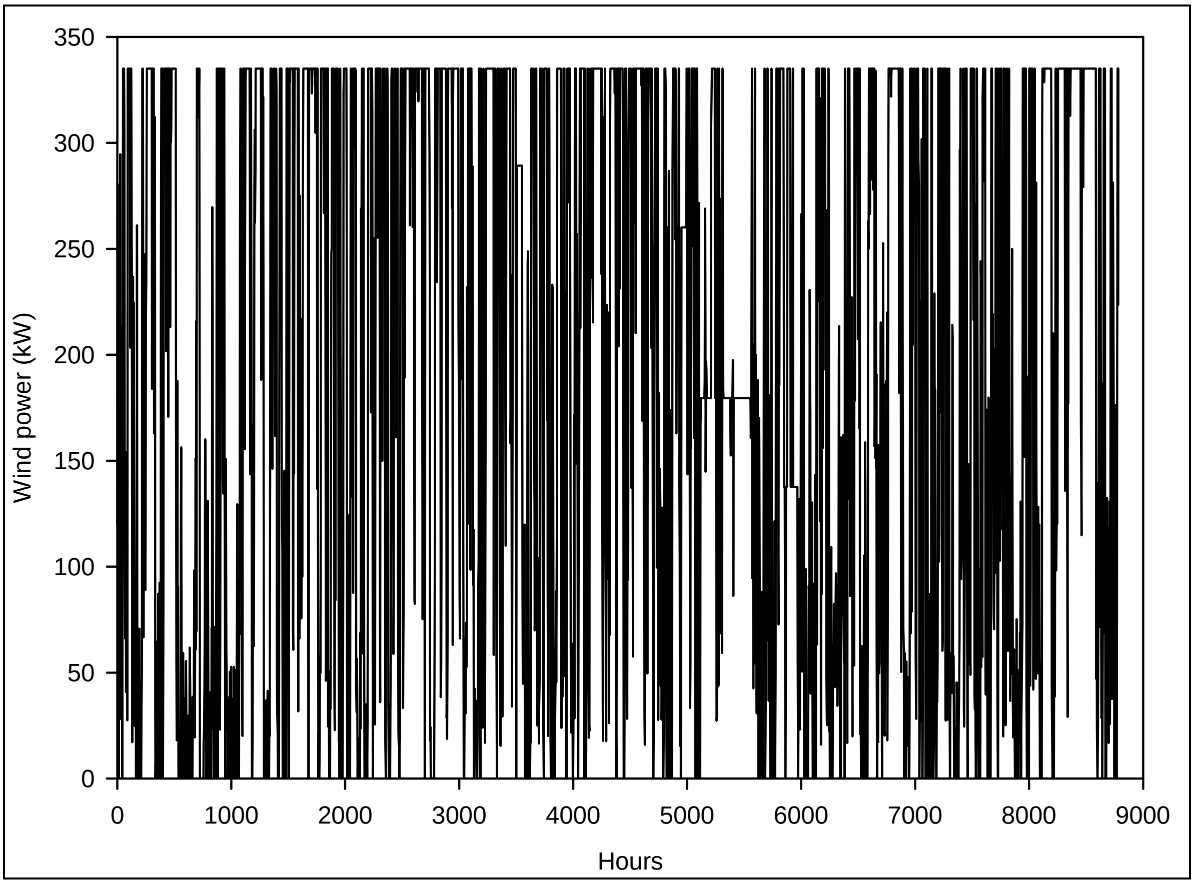

Figure 5. Annual power output

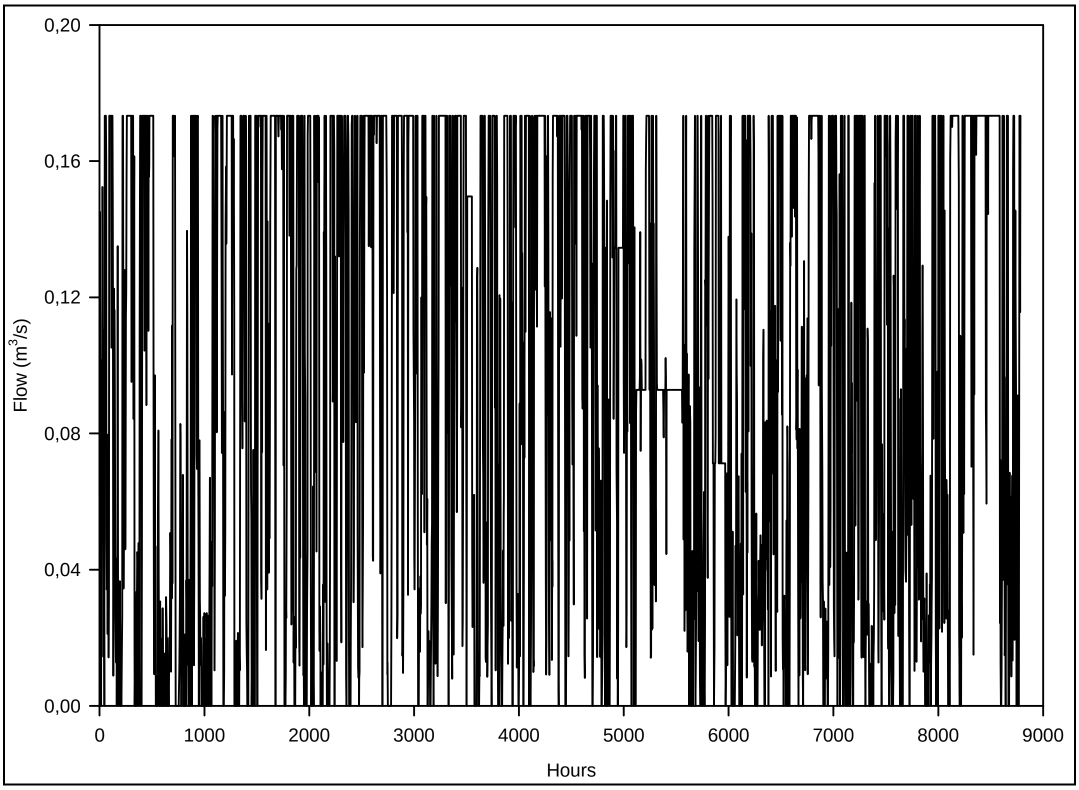

Figure 6. The quantity of water which elevates from the lower to the upper reservoir.

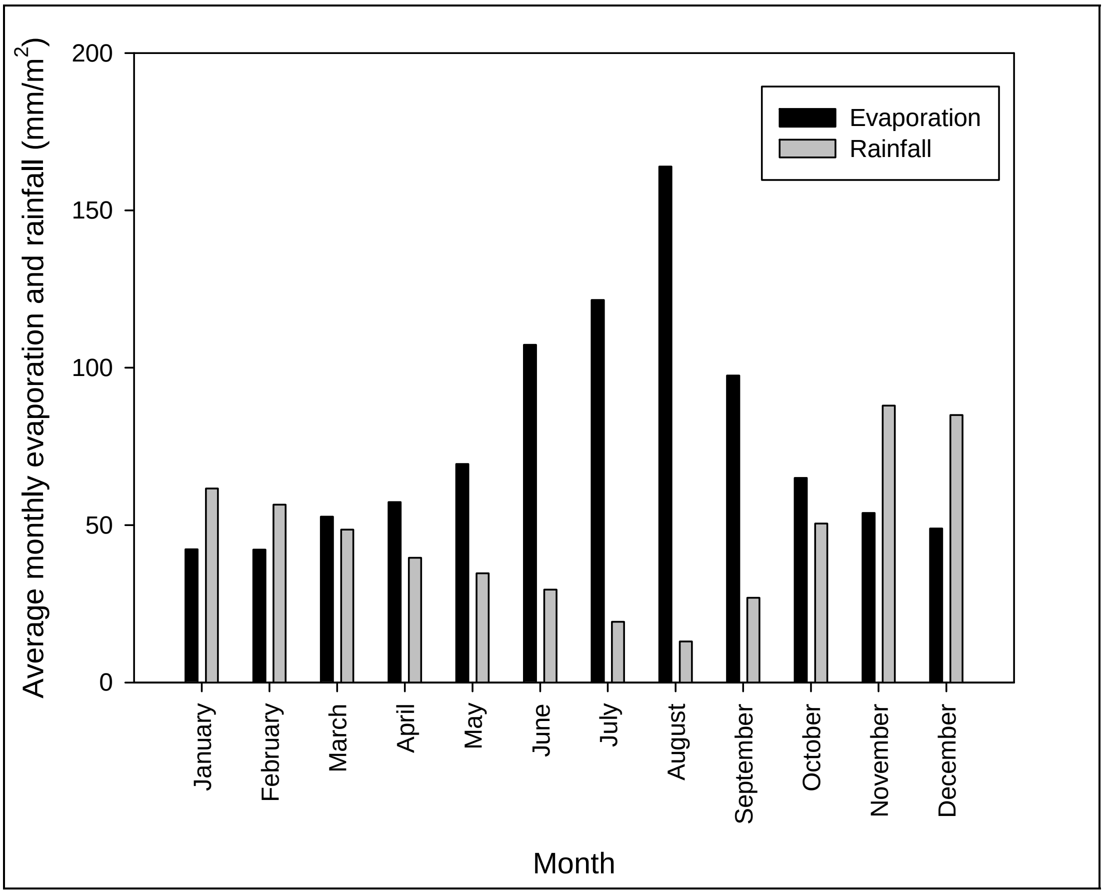

Figure 7. Monthly rainfall and evaporation for the period 1951-1997

The Penman equation describes evaporation (E) from an open water surface, and was developed by Howard Penman in 1948. Penman's equation requires daily mean temperature, wind speed, relative humidity, and solar radiation to predict E.The Penman-Monteith method refers to the use of an equation for computing water evaporation from a surface. It was proposed and developed by John Monteith in his seminal paper [20] in which he illustrated its thermodynamic basis with a psychometric chart. Monteith’s derivation was built upon that of Howard Penman [21] in the now well-known combination equation given as

$$\lambda E = \frac{\Delta * (R_n - G) + \gamma * \lambda * \mathrm{E}_\alpha}{\Delta + \gamma} \qquad (9)$$

where λE is the evaporative latent heat flux in MJ m^{-2} d^{-1}, λ is the latent heat of vaporization in MJ kg^{-1} [λ = 2.45 MJ kg^{-1} at a temperature of 20ºC and taken as a constant for most purposes], Δ is the slope of the saturated vapor pressure curve [$\partial e^o / \partial T$, where e^o is saturated vapor pressure in kPa and T is the temperature in ºC, usually taken as the daily mean air temperature], R_n is net radiation flux in MJ m^{-2} d^{-1}, G is sensible heat flux into the soil in MJ m^{-2} d^{-1}, γ is the psychrometric constant in kPa $ºC^{-1}$ [~0.066 kPa $ºC^{-1}$ but proportional to barometric pressure relative to standard atmospheric pressure (101.3 kPa), and E_a is the vapor transport flux in mm d^{-1} [1.0 mm d^{-1} ≈ 1.0 kg m^{-2} d^{-1}].

C. **Results**

The choice of water turbine is determined primarily by the size of head. In our project the Pelton turbine is most suitable because Pelton turbines are suited to high head, low flow applications. This turbine is simple to manufacture, are relatively cheap and have good efficiency and reliability. In addition is characterized by a relatively flat efficiency curve. Bucket-like blades are attached to its runner, subdivided into two half-shells respectively by a sharp edge. The water flow may be influenced through one or several nozzle jets that may be controlled finely. The water leaves the needles, hitting the subdivided runner blades tangentially. The water jet is deflected in the hollows of the blades by almost 180 degrees, transmitting its energy to the turbine. During this process the entire pressure energy of the water is converted into kinetic energy when leaving the nozzle. In order to stop the wheel a valve is used to shut off the water completely [22, 23]. Presently Pelton turbines are available within the following ranges: heads of between 100 and 500 meters, flows between 0.06 and 1.0 m^3/s, nominal power outputs of 50 to 2000 kW [24].

The usable flow rate Q_u (the amount of flow you can divert for power generation) calculated with the equation (10):

$$Q_u = \frac{SV_a}{24\frac{h}{d} \cdot 366\frac{d}{y} \cdot 60\frac{min}{h} \cdot 60\frac{s}{min}} \approx 0.1\ m^3/s \qquad 10$$

or the hydroelectric plant, the energy output is calculated according to Ref. [25]

$$E_H = \int_0^{t=T} g \cdot P_{turbine} \cdot \eta_h \cdot Q_u \cdot (H - h_f) \cdot dt \qquad 11$$

where η_h is the overall efficiency of the hydroelectric generating units and Qu [m^3/s] is the total flow at time t.

The $P_{turbine}$ is equal to 85.9 kW and the EH = 659 MWh/year. The most important question in planning a hydropower system is how much energy can be expected from the site and whether or not the site will produce enough power to meet your energy needs. For a typical home in Plaka, the total energy requirement is approximately 5520 kWh per year (Table 2) [26]. The village has 60 houses so the total electrical energy consumption per year is 332 MWh. The energy for street lighting is approximately the 20% of households’ consumption. The total annual electricity consumption is 398 MWh per year. With the rest of energy is possible to provide power in a School, Church and last but not least in a topical telecommunications systems.

TABLE II. AVERAGE MONTHLY ENERGY DEMAND OF TYPICAL HOUSEHOLD ON PLAKA [26]

Appliance	**Daily energy consumption per appliance (kWh)**		
	Winter	***Spring –Autumn***	***Summer***
Food freezer	1.35	1.89	2.7
Refrigerator-freezer	3	3.5	4
Washing machine	0.25	0.25	0.25
Dishwasher	1	1	1
Tv	0.3	0.3	0.3
Lighting	1	0.7	0.4
Other	0.75	0.75	0.75
Cook	3	3	3
Heater	4.5	4	4
Total daily energy consumption	15.15	15.39	15.4
Annual energy consumption per household.	5519.7		

III.CONCLUSIONS

The objective of this work is to model Wind/Hydro hybrid power systems using the long term wind resource of Rhodope for electrification of isolated small villages like Plaka. It demonstrated that via the installation of a wind powered pumped hydro storage system is possible to supply power on a remote small village. The proposed system, based on the use of medium wind turbine (330 kW), while wind energy sources cannot provide energy on demand independently, they can be used together to form the pumped storage system and meet demands collectively. The simulation results indicate that the stored hydraulic energy is capable to produce guaranteed electric power in a water turbine for an agreed period.

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