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ANALYSIS OF PUMPED HYDROELECTRIC STORAGE FOR A WIND/PV SYSTEM FOR GRID INTEGRATION

G. Notton, V. Lazarov, L. Stoyanov

Abstract: This paper deals with the pumping storage system analysis. The water reservoir serves for daily and seasonal energy storage, thus basically solving the problem of energy storage, which is the biggest problem of wider use of renewable energy sources. The electrical energy produced in excess by the renewable energy system is converted in potential energy by pumping water to a higher elevation where it can be stored indefinitely and then released to pass through hydraulic turbines and generate electricity. The estimation of the stored energy, the nominal electrical power of the hydroelectric plant and the evaporation rate of the water reservoir is presented.

Keywords: solar energy; wind energy; hybrid systems; pumped storage.

1. INTRODUCTION

In small electrical grids with limited or no connectivity to a large scale power system some difficulties appear as to keep control of voltage and frequency. In such an isolated system, we note numerous network failures and a limitation of the renewable energy part due to the random nature of the solar and/or wind source. Thus the initiative to diversify the energy sources is hindered. This is the case with the Corsica Island in the Mediterranean Sea, which is not connected to the French mainland electrical grid (and only a small connection with Sardinia).

The combination of renewable resources with energy storage can be a solution because it can increase the value of photovoltaic (PV) and wind-generated electricity, making supply coincident with periods of peak consumer demand. Energy storage systems have different application as to follow load, stabilize voltage & frequency, manage peak loads, improve power quality, defer upgrade investments, and support renewables. Fig. 1. shows the power and discharge time requirements for a variety of storage applications in the utility industry.

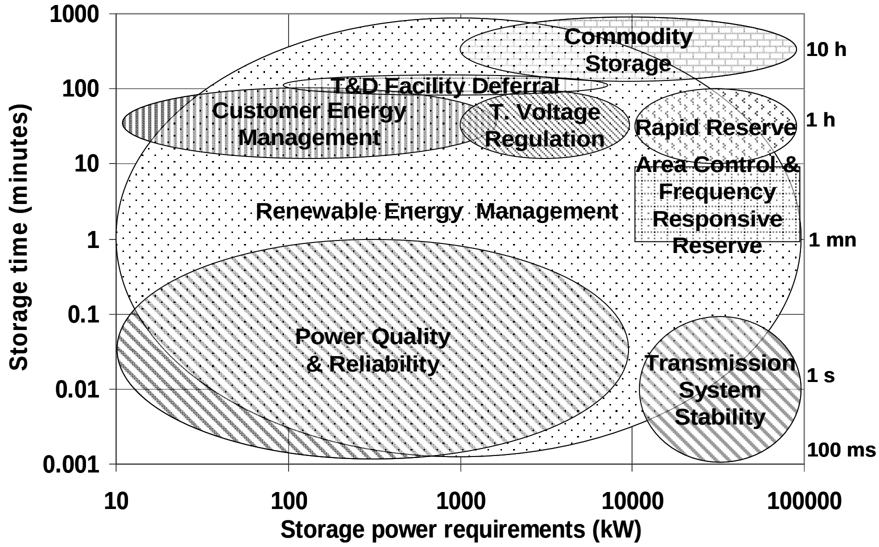

Fig. 1. Power and discharge time requirements for a variety of storage applications

2. OVERVIEW

The pumped storage is a system of generating electricity, also known as hydroelectric storage, which uses water that has been pumped into an elevated reservoir during the hours of low consumption to generate electricity during hours of peak demand. This type of hydroelectric system is used by some power plants for load balancing.

The method stores energy in the form of water (potential mechanical energy) from a lower elevation reservoir to a higher elevation. In a conventional electrical system, the low-cost off-peak electrical power is used to run the pumps and the stored water is released during periods of high electrical demand, generally with a cost benefit. In a “Renewable energy system”, at time of low electrical demand, excess generation power produced by the renewable energy system (wind turbine and/or photovoltaic system) is used to pump water into a higher reservoir and then, when there is a higher demand, the water is released back in the lower reservoir through a turbine, generating electricity.

There are two possibilities:

- two water ways: one for the pumping, the other for the turbine;
- one unique water way : a reversible machinery (usually a Francis Turbine design) (Fig. 2) is used for both pumping and generating; it is designed as a motor and pump in one direction and as a turbine and generator in opposite rotation (Fig. 3)

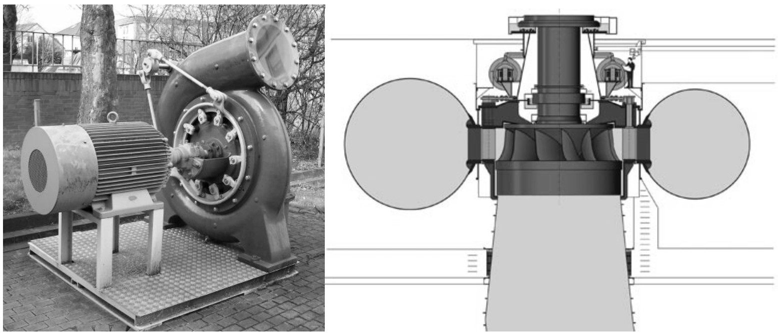

Fig. 2. A Francis Turbine

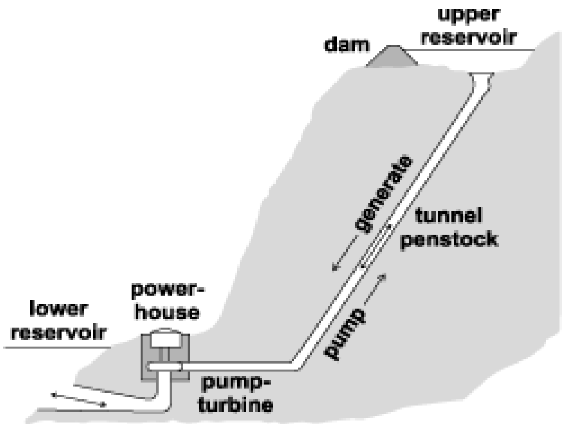

Fig. 3. Schematic of a conventional pumped-storage development with one reversible pump.

The station is located underground if the geological conditions are favourable, otherwise it is situated on the lower reservoir. Various pumped storage plants exist worldwide with power from about 1 MW (RHE Lepenica, 1985, Croatia) to 2700 MW (Kannagawa, 2005, Japan) [1]. Pumped hydro is available at almost any scale with discharge times ranging from several hours to a few days.

The advantages of such systems are [2]:

- More than 100 years of experience;
- High efficiency: in the 70% to 85% range.
- Multipurpose facilities;
- Environmental friendly;
- CO_2- avoiding;
- Highest availability compared to other technologies;
- Quick response to load variation (some seconds) and reserve capacity.

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70% to 85% of the electrical energy used to pump the water into the elevated reservoir can be regained.

A comparison of various storage means is shown in Fig. 4 [3, 4] in term of ratings. We note that hydro-pumped system (PSH) is adapted for high rated power (400 to 4000 MW) with high discharge time between 10 and 100 hours.

The capital cost is an important economic parameter, so the total ownership cost (including the impact of equipment life and O&M (Operation & Maintenance) costs) is an interesting index for a complete economic analysis. A comparison from an economic point of view of the energy storages is shown in Fig. 5 [3]. The cost of a PSH system is between 1000 and 2000 $/kW.

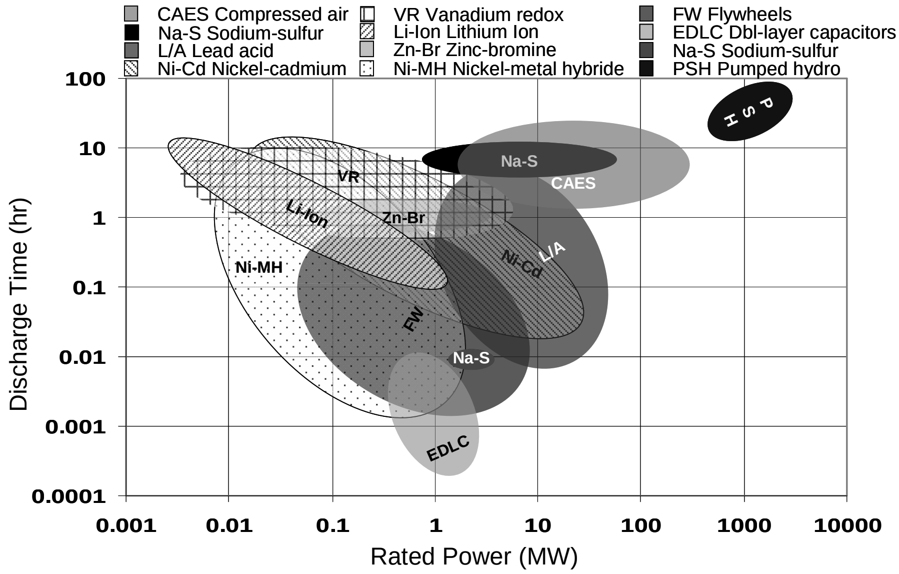

Fig. 4. Storage systems ratings [3]

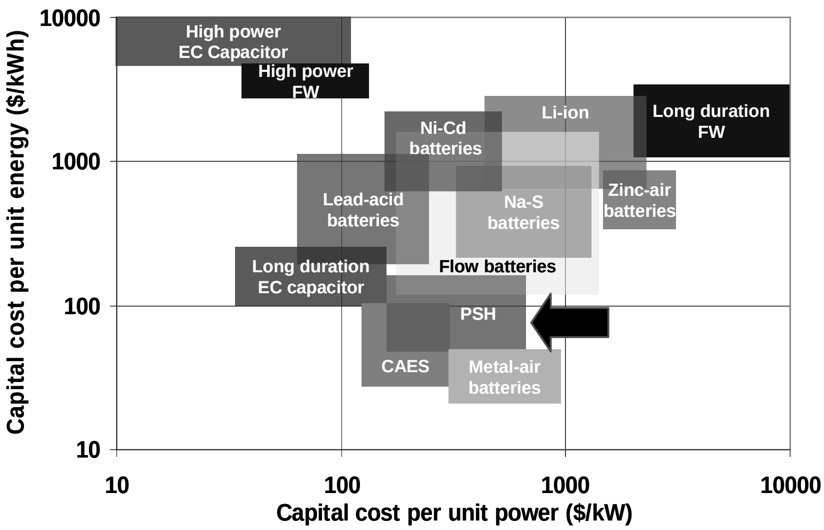

Fig. 5. Storage systems costs [3].

Efficiency and cycle life are two important parameters to consider along with other parameters. Both of these parameters affect the overall storage cost. Low efficiency increases the effective energy cost as only a fraction of the stored energy could be utilized. Low cycle life also increases the total cost as the storage device needs to be replaced more often. The present values of these expenses need to be considered along with the capital cost and operating expenses to obtain a better picture of the total ownership cost for a storage technology. Fig. 6. illustrates this influence for various storage technologies. The lifetime (for depth of discharge (DOD) 80%) for such a pumped hydro system is one of the highest available with storage means.

Per-cycle cost can be the best way to evaluate the cost of storing energy in a frequent charge/discharge application, such as load levelling.

Fig. 7 shows the capital component of this cost, taking into account the impact of cycle life and efficiency. For a more complete per-cycle cost, one needs to also consider O&M, disposal, replacement and other ownership expenses, which may not be known for the emerging technologies. We note that the capital cost per cycle is largely lower than for other existing storage systems.

There is over 100 GW of pumped storage in operation world wide, which is about 3 % of global generation capacity (32 GW in Europe, 21 GW in Japan, 19.5 GW in USA, and others in Asia and Latin America) [5-7]. Pumped storage plants are characterized by long construction times and high capital expenditure.

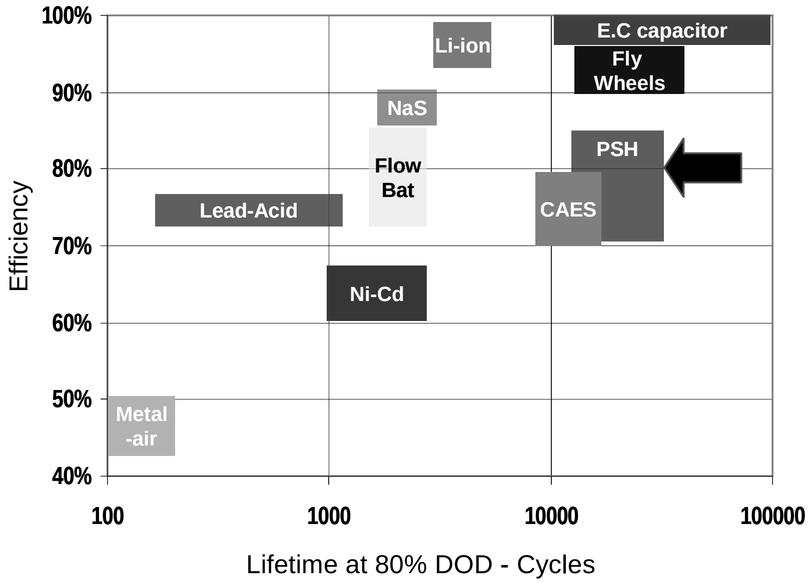

Fig. 6. Life efficiency of various storage systems [3].

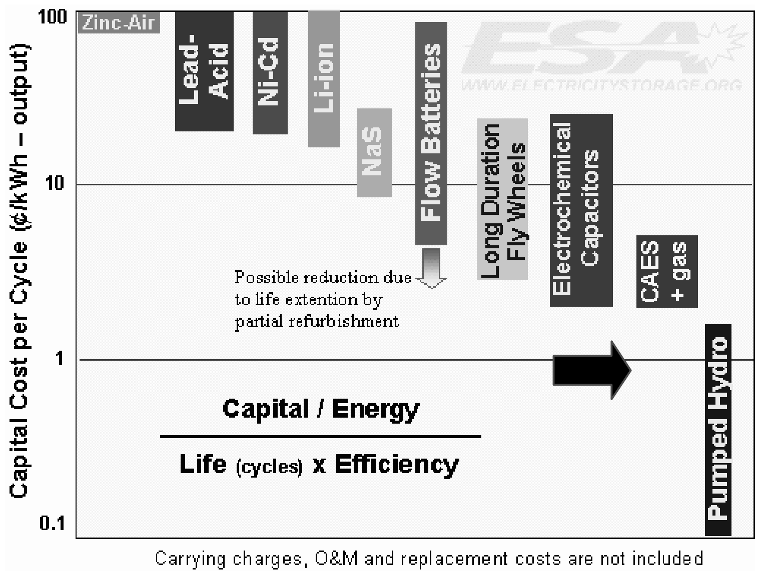

Fig. 7. Per-cycle cost for various storage systems [3].

Pumped storage is the most widespread energy storage system in use on power networks. Its main application is for energy management, frequency control and provision of reserve.

3. APPLICATION WITH RENEWABLE ENERGY SYSTEM

Using a hydro-pumped storage allows to improve the quality of the provided electricity and to reduce the peak power of the other energy generating systems. This system flattens out the load variation on the power grid, and permits thermal power stations that provide base-load electricity to continue operating at peak efficiency while reducing the need for peaking power plants that use costly and polluting fuels. Moreover, a pumped storage system helps control electrical network frequency and provides reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. The hydro-pumped system can respond to load changes within seconds. These machines generate in synchronization with the network frequency, but operate asynchronously (independent of the network frequency) as motor-pumps.

A new use for pumped storage is to level the fluctuating output of intermittent power sources. The pumped storage absorbs load at times of high output and low demand, while providing additional peak capacity. In certain jurisdictions, electricity prices may be close to zero or occasionally negative (Ontario in early September, 2006), indicating there is more generation than load available to absorb it; although at present this is rarely due to wind alone, increased wind generation may increase the likelihood of such occurrences. It is particularly likely that pumped storage will become especially important as a balance for very large scale photovoltaic generation. The principle is illustrated in Fig. 8.

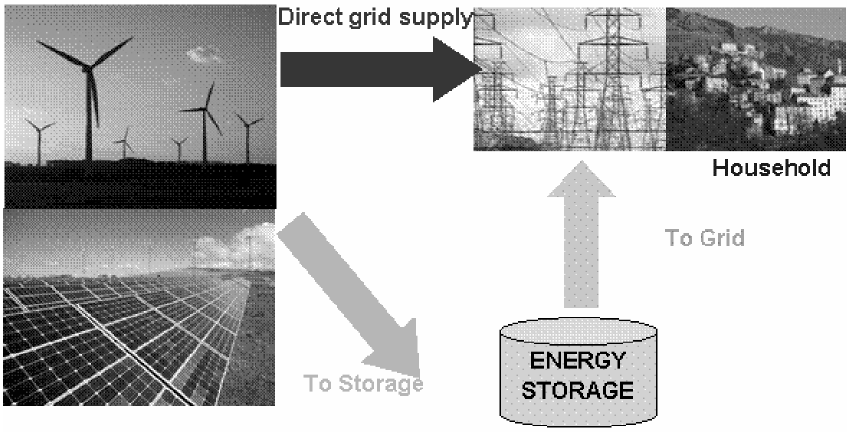

Fig. 8. Principle of coupling between renewable energy sources and hydro-pumped system.

The typical overall efficiency of hydro-storage systems is between 65% and 77% [4, 8] with a maximum depth of discharge up to 95%. Kaldellis *et al* [4] showed that this type of system for island autonomous electrical networks is the optimal solution for big size islands and for small and medium sized islands; it appears to be the best solution for autonomy of 24 hours.

4. STORED ENERGY AND MACHINES POWER ESTIMATION

The relative low energy density of pumped storage system requires either a large body of water or a large variation in height. For example, 1000 kg of water (1 m^3) at the top of 100 m tower has a potential energy of about 0.272 kWh. The only way to store a significant amount of energy is by having a large body of water.

We consider the system presented in Fig. 9. The developed excel software estimates the stored energy and the turbine and pump peak powers for a given case study. The input data are:

- upper tank altitude: h_{upper}
- lower tank altitude: h_{lower};
- pump or turbine altitude h_{pump} or $h_{turbine}$;
- the water tanks volume V;
- the length and diameter of upstream and downstream tubes: L_1, L_2, D_1, D_2;
- the maximum water flow rate into the turbine and the pump (or the reversible pump) Q_{pump}, $Q_{turbine}$;
- the roughness height of the tube ε (equal to 0.1 mm)

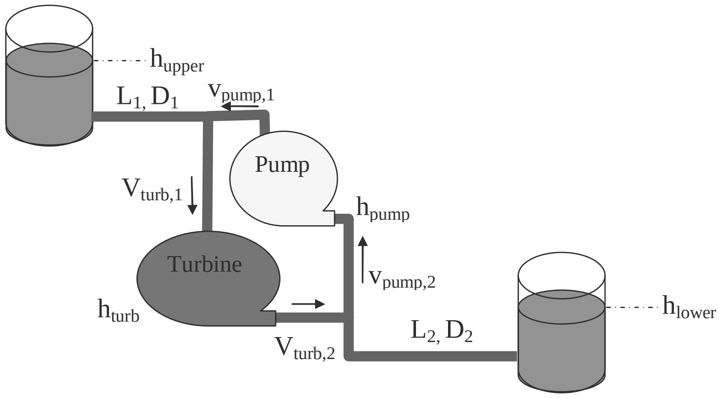

Fig. 9. Schematic presentation of the studied system.

We calculate:

- the maximum water speed in each tube: $v_{pump,1}$, $v_{turbine,1}$:

$$v_{pump,1} = 4Q_{pump} / \left(pD_1^2 \right) \text{ and}$$
$$v_{turbine,1} = 4Q_{turbine} / \left(pD_1^2 \right) \quad (1)$$

- the Reynold number and the flow regime with υ is the kinematic viscosity taken equal to 1.10^{-6} m/s²:

$$\Re e_{pump} = v_{pump}.D/n \text{ and}$$
$$\Re e_{turbine} = v_{turbine}.D/n \quad (2)$$

- the Darcy friction factor λ calculated using the Swamee-Jain equation [9] which estimates Colebrook' equation with 2-5% error and given by :

$$l = 0.25 \Big/ \left[Log_{10} \left(\frac{e}{3.7 \times D} + \frac{5.74}{\Re e^{0.9}} \right) \right]^2 \quad (3)$$

- the Darcy-Weisbach coefficients J_1 and J_2 (m) given by :

$$J_1 = l_1 \frac{L_1}{D_1} \frac{v_1^2}{2g} \text{ and } J_2 = l_2 \frac{L_2}{D_2} \frac{v_2^2}{2g} \quad (4)$$

- the manometric height at each tank H_{upper} and H_{lower}:

$$H_{upper} = h_{upper} + \frac{p_{atm}}{rg} \text{ and}$$
$$H_{lower} = h_{lower} + \frac{p_{atm}}{rg} \quad (5)$$

where p_{atm} is the atmospheric pressure ($1.013.10^5$ Pa) and ρ the water density (1000 kg.m^{-3})

- the manometric heights upstream and downstream of the pump and the turbine are given by :

$$H_{down,turbine} = H_{upper} - J_{turbine,1} \quad (6)$$
$$H_{up,turbine} = H_{lower} + J_{turbine,2} \quad (7)$$
$$H_{down,pump} = H_{lower} - J_{pump,2} \quad (8)$$
$$H_{up,pump} = H_{upper} + J_{pump,1} \quad (9)$$

- the hydraulic power of the pump and the turbine are given by :

$$P_{turbine,hydraulic} = rg\left(H_{down,turbine} - H_{up,turbine}\right)Q_{turbine} \quad (10)$$
$$P_{pump,hydraulic} = rg\left(H_{up,pump} - H_{down,pump}\right)Q_{pump} \quad (11)$$

- the electrical powers are given by :

$$P_{turbine,elec} = P_{turbine,hydraulic} \times h_{turbine} \times h_{alternator} \quad (12)$$
$$P_{pump,elec} = P_{pump,hydraulic} / \left(h_{pump} \times h_{motor} \right) \quad (13)$$

- the gross stored energy, generated by the reservoir, is [10]:

$$E_{gross} = rg\left(H_{upper} - H_{lower}\right) \quad (14)$$

- the total daily hydraulic energy (kWh) which the renewable system can produce at the outlet of the pumping system is obtained by [10]:

$$E_{H,daily} = \frac{rg\left(H_{down,turbine} - H_{up,turbine}\right) \times Q_{turbine}(m^3/day)}{1000} \quad (15)$$

5. WATER TANK EVAPORATION RATE ESTIMATION

Fig. 10 shows the principle diagram of the renewable plant with characteristic elements.

For calculating the hydraulic balance of the pump/turbine system, several physical data are needed or must be calculated as:

- evaporation rate
- watershed flow rate
- infiltration

To determine the evaporation rate, which can be important particularly in arid or sunny areas, the main parameters to calculate are:

- the convective heat transfer coefficient h_c;
- the mass transfer coefficient K_E
- the water surface temperature T_{ws}
- and finally the evaporated water rate E.

A study made by Sartori [11] shows that various methods are available to calculate the evaporation flow rate. It has been shown that the relative humidity must be taken into account for a better accuracy. A similar more recent work [12] confirms the variability of the results obtained by the various models. In this work, the evaporation rate estimation must stay simple because its influence on the energy system behaviour is not important enough to necessitate a very thorough work.

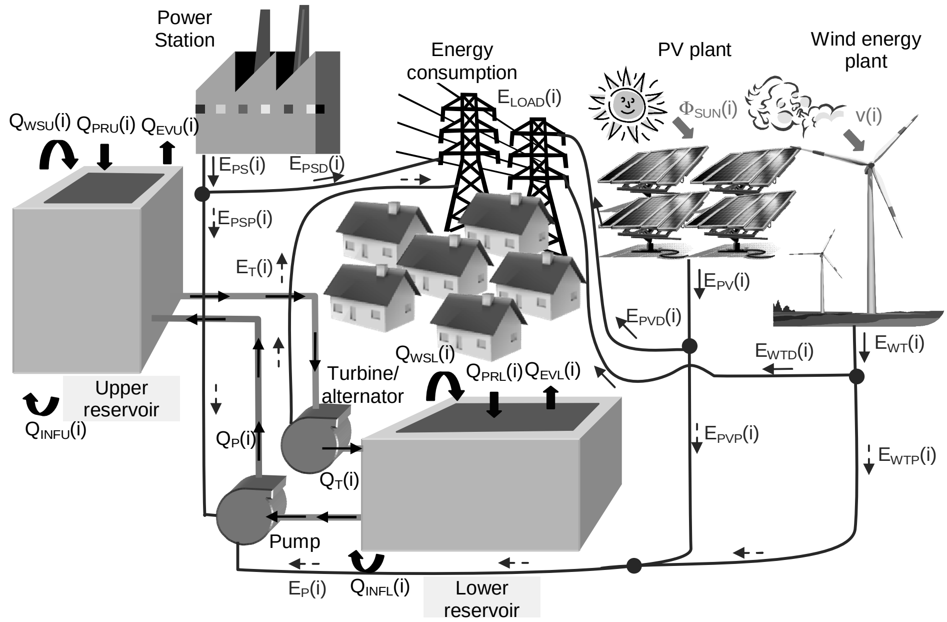

Fig. 10. Principle diagram of the renewable plant with characteristic elements

Watmuss et al [13] suggested to use as convective heat transfer coefficient the following expression:

$$h_c = 2.8 + 3.0v \tag{16}$$

with v the wind speed. The authors converted this equation taking into account that the wind speed is generally measured at 10 m height. Their fitted equation became:

$$h_c = 3.1 + 2.1v \tag{17}$$

Eq. (17) is used in this work. The mass transfer coefficient, as expressed by the exact form of Chilton-Colburn analogy may be written as follows [14]:

$$K_E = b\left(\frac{h_c}{rC_p}\right) \text{ with } b = \left(\frac{p_T}{P_a}\right)\left(\frac{Pr}{Sc}\right)^{0.67} \tag{18}$$

P_a and P_T are respectively the partial pressure of air and the total pressure. The simplified form of Chilton-Colburn Analogy assumes the ratio of Pr to Sc is equal to one and ignores the effect of water vapour pressure on the partial pressure of air (P_a=P_T). Under such condition, β will be equal to 1 and equation (18) simplifies to:

$$K_E = h_c / \left(rC_p\right) \tag{19}$$

This simplification is called the Lewis hypothesis, only valid for the air and used by Belarbi and Saïghi [15] to estimate the evaporation rate of a water surface.

The saturated and partial water vapour pressures (in Pa) are given by [12]:

$$P_{s,wv}(T) = 1000 \times 0.6108 \times exp\left(\frac{17.27 \times (T - 273.15)}{(T - 273.15) + 237.3}\right) \tag{20}$$

$$P_v(T) = h_r \times P_{s,vw}(T) \tag{21}$$

The water density and its specific heat capacity depend on the absolute humidity X and are given by:

$$X = 0.6221 \times \frac{P_v(T)}{[P_T - P_v(T)]} \tag{22}$$

$$r = \frac{p_T - p_v(T)}{287.05T} + \frac{p_v(T)}{461.495T} \tag{23}$$

$$C_p = C_{p,wv} + XC_{p,dryair} \tag{24}$$

The evaporation from a water body is estimated as the difference between energy inputs and outputs measured at a site. The energy loss through evaporation represents a major component of the energy balance in a typical water body.

The temperature of the water surface is calculated from an energy balance [15-17]:

$$R_n = L_{w,v}E + H + G \qquad (25)$$

A part of the radiation R_n is used to evaporate the water available at the water surface and creates the latent heat flux $L_{w,v}E$ where E is the evaporation rate and $L_{w,v}$ the latent heat of water vaporization. The rest is dissipated in heat into the air by convection (H sensible heat) or stored into water (G conductive heat flux).

The water latent heat flux for vaporization is expressed from Harrison formulation [18]:

$$L_{w,v} = 2.501 - 2.361.10^{-3}T \qquad (26)$$

The storage of the heat into the water during a one hour period is generally small compared with the other heat fluxes [15-16] and G can be neglected. Then Eq. (20) becomes:

$$R_n = L_{w,v}E + H \qquad (27)$$

$$R_n = (1-a)R_g + es\,(T_a - 6)^4 - esT_{ws}^4 \qquad (28)$$

with R_g, the global solar radiation, α the albedo of the water surface (≈ 0.08)[19], ε the water surface emissivity (≈ 0.98) [20] and σ the Stefan-Boltzmann constant, T_{sw} and T_a are the water surface and air temperatures.

$$H = h_c\,(T_{ws} - T_a) \qquad (29)$$

The latent heat flux is calculated by the Stefan method (simplified expression of the Fick theory) based on the mass transfer or bulk transfer theories.

$$L_{w,v}E = \frac{L_{w,v}K_E M_w}{RT_a}\left[P_{s,wv}(T_{ws}) - P_v(T_a)\right] \qquad (30)$$

with M_w, the molecular mass, $P_{s,wv}$ saturated water vapour pressure and P_v water vapour partial pressure.

Thus, in replacing equations (28), (29) and (30) into equation (27), the energy balance becomes:

$$(1-a)R_g + es(T_a - 6)^4 - esT_{ws}^4 - h_c(T_{ws} - T_a) = \frac{L_{w,v}K_E M_w}{RT_a}\left[P_{s,wv}(T_{ws}) - P_v(T_a)\right] \qquad (31)$$

Thus, we can calculate, using a method of dichotomy, the water surface temperature at each hour, from the following measured data :

- wind speed v
- ambient temperature T_a
- relative humidity h_r
- horizontal global irradiation R_g

The next step consists in estimating the evaporation rate and various methods are available to reach this goal with more or less precision. Several formulations have been compared [11-12]. We decided to use for our study the Penman method which is based in physical principles and gives values that should serve for most project studies [15-16, 19]. The Penman formulae can be expressed by:

$$L_v E = \frac{\Delta}{\Delta + g}R_n + \frac{h_c}{(\Delta + g)}\left(P_{s,wv}(T_a) - P_v(T_a)\right) \qquad (32)$$

where γ is the psychometric constant given by [19]:

$$g = (1628.6 \times P_a)/L_{w,v} \qquad (33)$$

Δ is the slope of vapour pressure versus temperature curve given by [15-16]:

$$\Delta = \left(P_{s,wv}(T_{ws}) - P_{s,wv}(T_a)\right)/(T_{ws} - T_a) \qquad (34)$$

From hourly meteorological data of Ajaccio (wind speed, solar irradiation, ambient temperature and relative humidity), we calculated the evaporation rate. The results for one year are presented in Fig. 11. We note that sometimes during the night the evaporation is negative i.e. the water surface temperature is below the dew point temperature and condensation occurs.

At last, we estimated the monthly average values of the daily evaporation rate with the meteorological data for two stations – Ajaccio (France) and m. Botev (Bulgaria) with a colder climate (Fig. 12). We note that the evaporation phenomenon is not negligible and influences the energy balance of the system.

6. CONCLUSION

The pumping storage is the most widely implemented large-scale electrical energy storage. PHS is a mature technology with large volume, long storage period, high efficiency and relatively low capital cost per unit of energy.

We estimated the stored energy and the pump and turbine peak powers according to the characteristic of the water storage.

Then, the influence of the evaporation phenomenon at the water surface has been estimated.

This work gives an idea for some procedures in the pumping storage analysis before its integration in electrical power system with renewable energy sources.

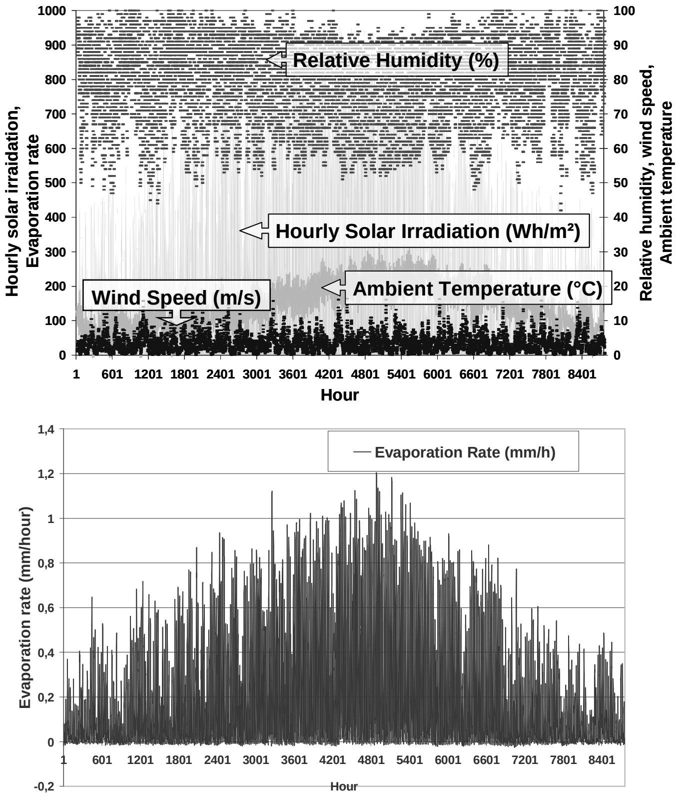

Fig. 11. Meteorological parameters and estimated evaporation rate for Ajaccio

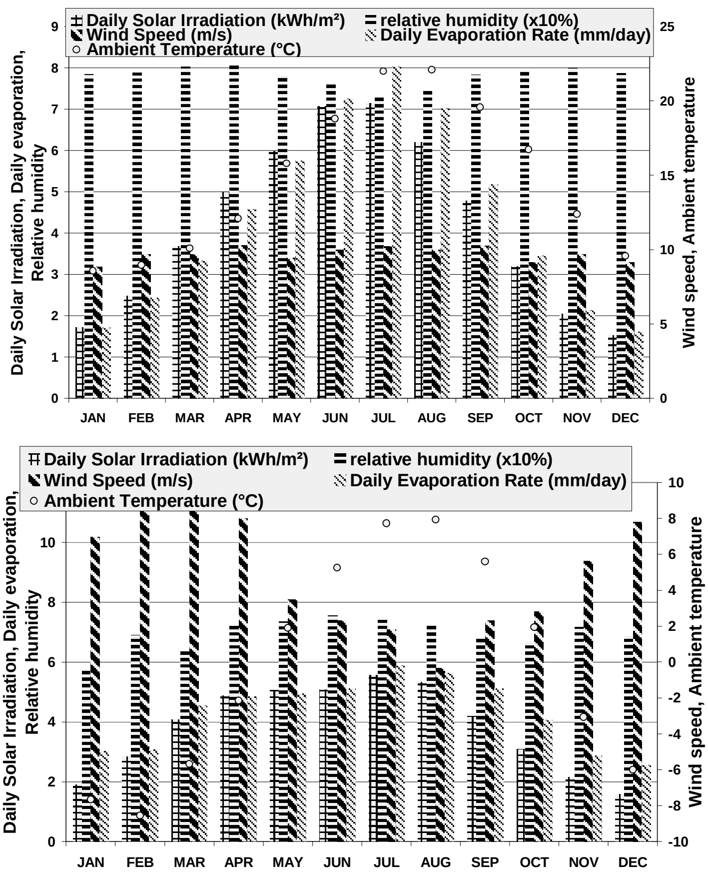

Fig. 12. Monthly average values of the daily evaporation rate for Ajaccio and Botev

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АНАЛИЗ НА ПОМПЕНО АКУМУЛИРАЩА ВОДНОЕЛЕКТРИЧЕСКА ЦЕНТРАЛА КЪМ СИСТЕМА С ВЕТРОГЕНЕРАТОР И ФОТОВОЛТАИК ЗА ВНЕДРЯВАНЕ В ЕЛЕКТРИЧЕСКАТА МРЕЖА

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Резюме: Тази статия има за цел анализ на помпено акумулираща водноелектрическа централа за запазване на енергия. Водният резервоар има за цел съхраняването на енергия за дни или сезони като по този начин се улесни разпространението на възобновяеми източници на енергия. Електричеството произведено в повече от хибридната система с възобновяеми източници на енергия се превръща в потенциална енергия посредством изпомпване на вода в горния резервоар, където тя може да се съхранява безкрайно много и в последствие да премине през хидравличната турбина произвеждайки електроенергия. Оценката на запасената енергия, на номиналните мощности на хидроенергийния възел и на загубите при изпаряване от водния резервоар са представени.

Ключови думи: слънчева енергия, вятърна енергия, хибридни системи, запазване на енергия чрез изпомпване

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