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Wind-hydro pumped storage systems to meet lebanese electricity demand

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Abstract - *Lebanon is facing currently anacute energy crisis, due tolack of domestic energy resources, reduced production capacities and a growing demand for energy. Relying on wind energy could reduce the impact of this crisis. However, continuous change in wind speed from calm to stormy introduces challenges. One possible solution to address these challenges is to introduce new storage facilities or to use storage capabilities already available in the power generation system. Existing hydro power plants with large reservoirs or pumped storage hydro power plants are suitable for this purpose. Furthermore, Lebanon has a fairly high wind energy potential and hydro power resources. This paper is an attempt to analyze the design of a pumping station and the performance of a hybrid wind-hydro power plant, in three hydraulic plants to produce electricity in Lebanon (Markabi, Awali and Joun), in order to choose the most suitable plant to store electrical power. An economic analysis and an evaluation of the amount of water that could be pumped in each of the hydraulic plants are carried out in this study, in order to select the most suitable hydraulic plant to store the electricity surplus. Moreover, this study presents an economic evaluation of the implementation of wind turbines in Lebanon. It is shown that Markabi is the most suitable plant to store electrical power.*

Résumé – *Le Liban fait face actuellement à une grave crise énergétique, due à un manque de ressources d'énergie domestique, des capacités de production réduites et une demande énergétique en constante augmentation. Compter sur l'énergie éolienne peut réduire l'impact de cette crise. Cependant, un continuel changement dans la vitesse du vent de calme à orageux, engendre de nouveaux défis. Une solution possible pour parer à ces défis est d'introduire de nouvelles installations de stockage ou bien utiliser les capacités de stockage déjà disponible dans le system de génération d'énergie. Des centrales électriques hydrauliques existantes avec de grands réservoirs ou des centrales électriques de pompage hydraulique de stockage sont appropriées à cette fin. En outre, le Liban a un assez haut potentiel d'énergie éolienne et des ressources d'énergie hydraulique. Cet article est une tentative d'analyser le la conception d'une station de pompage et les performances d'une centrale électrique hybride hydraulique-vent, dans trois installations hydrauliques pour produire l'électricité au Liban (Markabi, Awali et Joun), pour choisir l'usine la plus appropriée pour stocker l'électricité. Une analyse économique et une évaluation de la quantité d'eau qui pourrait être pompée dans chacune des installations hydrauliques sont effectuées dans cette étude, pour choisir l'installation hydraulique la plus appropriée pour stocker l'excédent d'électricité.*

Keywords: Hybrid wind-hydro power - Wind potential - Wind energy - Lebanon.

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1. INTRODUCTION

Wind energy is one of the economic renewable sources and a valuable supplement to conventional energy sources. Wind energy technology was gradually improved since the early 1970s. By the end of the 1990s, wind energy has emerged as one of the most important renewable energy resources [1]. However, wind power suffers from an intermittent characteristic due to the own diurnal and seasonal patterns of the wind behavior. Using energy storage strategies will help wind turbines to follow closely a given production plan, to improve their participation to the market, or just for the optimization of wind power production.

There are many kinds of storage systems that have been applied for different purposes in many countries. Some of them are pumped hydro energy storage (PHES), thermal energy storage, battery storage systems and even hydrogen energy storage. Pumped storage predicts to be the most prominent operational option to support large wind installation and penetration, because it concentrates certain advantages, such as high capacity, availability and flexibility [2, 3].

On the Spanish island of El Hierro in the Canary Islands, a pumped storage system of 11.32 MW (4 Pelton turbines of 2.83 MW) coupled with a 11.5 MW wind farm can meet 80 % of the annual energy demand of the island [4].

In a power production system, pumped storage system fulfills the requirements for the quantity and quality indicators of distributed electricity, and they increase the operational safety of the whole system. Pumped storage hydropower can provide energy balancing, stability, storage capacity, and ancillary grid services such as network frequency control and, mainly, reserves (R1, R2, R3). This is due to the ability of pumped storage system plants, like all hydroelectric plants, to respond to load changes within seconds, helping instantaneously to maintain the balance between generation and net load so as to avoid brownouts, blackouts and overloads. Pumped storage projects also provide ancillary benefits such as firming capacity and reserves, reactive power, black start capability and spinning reserve. In the generating mode, the turbine-generators can respond very quickly to frequency deviations just as conventional hydro generators can, thus adding to the overall balancing and stability of the grid [5].

In addition, they are highly reliable and cost-effective, reducing electricity costs by using electricity produced at off-peak times when the price is lower. Systems demonstrate low maintenance costs and typically achieve one of the highest cycles per lifetime at some of the lowest costs [6].

There have been many studies conducted on the benefits of wind-hydro pumped storage systems. Some of the studies focus on the optimization of wind hydro pumped storage systems, while others focus on the modeling and analysis of wind - hydropumped storage systems [7, 8].

Cristorafi and his colleagues defined a methodology to indicate the relationship between the cost and magnitude of the combined wind turbine and pumped hydro system using real wind data and load data [7].

Guan and his colleagues proposed an optimization method for a hydro-thermal system [9]. Bakos studied how the hybrid wind-hydro power system in Ikeria Island, Greece, can produce cost-efficient electricity [10].

Castronuovo *et al.* proposed a methodology for combined wind power production and hydro-storage system. The increasing interest in the combined wind power production and hydro storage system engendered the application of the operational optimization approach [11].

Castronuovo *et al.* considered the concept of water storage availability in their method both to reduce the active power output variation and to get economic income with operating the wind farm. An hourly discretized optimization algorithm was proposed [12].

Kaldelis proposed a wind-hydro electric production system to meet the electricity demand of the Aegean Islands. He implemented a parametric analysis of the system to meet the demand of the islands with good local wind potential [13, 14].

Wind-hydro pump storage systems are made up of water reservoirs, hydro-turbines, hydro pumps generators/motors and wind turbines. Between 70% and 85% of the electrical energy used to pump the water into the elevated reservoir can be regained in this process [15]. The analysis of the wind power potential in Lebanon shows that it can play a vital role in reducing Lebanese electricity crisis[16, 17]. The potential for wind energy production in Lebanon has been shown to be especially possible in five sites.

More specifically, Daher El Baydar, Marjyoun, Cedars, Quaraoun and Klaiaat are the most suitable locations for wind energy production [16]. The geographical coordinates of these sites and the annual average wind speed at 10 m of height are given in **Table 1**. The wind turbine chosen to be installed generates maximum 7.5 MW. We found after a topographical study that 116 wind turbines could be erected in the five proposed wind farms.

After analyzing the wind energy potentials of the five different sites in Lebanon, it has been shown that the total expected electricity supply (current and wind farms supply) could be greater than the demand at night in all months except in August and September, and a significant percentage of the demand during daytime could be covered [17].

There still is a significant discrepancy between the amount of electricity demand and the amount of wind energy produced. To overcome such a problem, any surplus energy can be stored in storage units combined with a wind energy system. Regarding the capacity of Lebanon to use hydraulic energy as well as the advantages of the wind-hydro pumped storage systems, PHES can be the most suitable choice amongst other storage methods.

Table 1: The geographical coordinates of the selected sites and related average wind speed

Site	**Easting (m)**	**Northing (m)**	**Elevation above Sea level (m)**	V_m **(m/s)**
Daher El Baydar	706366	3682611	1524	9.50
Klaiaat	78097	3793722	5	7.80
Cedars	774278	3823977	916	7.30
Marjyoun	749026	3715206	760	9.35
Quaraoun	738724	3714557	855	6.9

In this paper, a wind power system is used together with a pumped-hydro storage system. In such a combined system, after meeting the demand, surplus energy or excessive energy is stored as potential energy in the pumped-hydro storage system by pumping water in a lower altitude to a higher altitude.

In other words, excessive energy is stored in a storage system during hours of low demand. If energy sources could not supply the energy demand at any time, potential energy in the pumped-hydro system, which is converted into hydro-electricity by releasing back the water from the upper reservoir through a hydro-turbine, could be used to supply the demand. Consequently, the wind power and the pumped-hydro storage systems operate together. This kind of combined system can be regarded as a reasonable way of both storing and keeping the energy continuity of the system while supplying high peak demand. Thus, wind energy potential of the region can be used efficiently.

The optimal operation of a pumped storage power plant has to fulfill the requirements of the power system such as the duration of on-peak generation periods, the amount of power generated, the amount of backup power, the range and cost of support services, etc. Concurrently, it has to provide the maximum economic effectiveness [18]

In the present work, we combined a pumped hydro storage system with wind power generation and designed a wind powered pumped hydro storage system to increase the electricity production in Lebanon. Three existing hydro projects with capacities between 34 and 108 MW could be used for the proposed hybrid system. In addition, a performance analysis of these three hydraulic power plants and an economic evaluation of a pumped hydro storage system in these three hydraulic plants are carried out in this paper in order to choose the most suitable hydraulic plant to store the excess of electricity. For the economic evaluation, we compared the number of requisite pumps and motors in each hydraulic plant and the cost of its installations and we chose the cheapest one. While for the performance analysis, we compared the volume of water that could be pumped from the lower reservoir to the upper reservoir, the absorbed energy by pumps, the size of the upper reservoir in each studied hydraulic plant and the evacuated volume. We chose the plant, which has the largest higher reservoir (to store more quantity of water) and the lowest absorbed energy by pumps and the highest volume of pumped and evacuated water.

Moreover, this paper presents an economic evaluation of the implementation of wind energy project in the five selected sites in Lebanon.

2. SITUATION OF THE LEBANESE ELECTRICITY SECTOR

The Lebanese electricity system is characterized by a weak performance in all analyzed aspects related to the sustainability of energy system [19]. A sustainable electricity system could be thought of in term of its energy and economic performance, its environmental impacts and its reliability. The basic requirement of an energy system is to generate power for everyone at an affordable price while ensuring that the power is clean, safe and reliable.

Lebanon is an indebted country that depends on oil imports to meet its various energy needs. The Lebanese electricity system lacks adequacy and security through its supply-demand deficit and a low diversity index [20]. In addition, it characterized by large economic inefficiencies. There have been many studies conducted to find ways to improve the sustainability of the Lebanese electricity system and to analyze it in order to examine their capacities to reach the requested objective.

Ibrahim et al. suggested and analyzed the use of natural gas instead of oil fuel to produce electricity in combined cycle gas turbine plants and the integration of wind energy potential in the grid to produce electricity [21].

El Fadel e*t al.* suggested and analyzed the improving of the transmission and distribution networks, the upgrading the conventional existing plants to achieve their design standards and shifting towards the use of natural gas and the use of the renewable energy sources, which are highly competitive alternatives to consider and support to meet the reliability of the electricity system [20].

Dagher *et al.* suggested and analyze the introducing of wind energy potential in the electricity system and using natural gas instead of fuel oil and diesel fuel [19]. In these three studies, the results show that the introduce of renewable energy source in the electricity generation system and the use of natural gas instead of fuel oil and diesel oil could improve the sustainability of the Lebanese electricity system by ensuring generation electricity with a clean, safe and reliable source and with an affordable price.

3. SITES AND DATA DESCRIPTION

The Quaraoun Reservoir is the largest reservoir in Lebanon. It is located in the Bekaa Valley on the Litani River at an elevation of 800 m, 86 km, upstream from the North of the Litani River into the Mediterranean Sea (Fig. 1). Quaraoun Reservoir has a surface area of 12 km^2, a maximum depth 60 m, mean depth of 19 m and total capacity is 222×10^6 m^3.

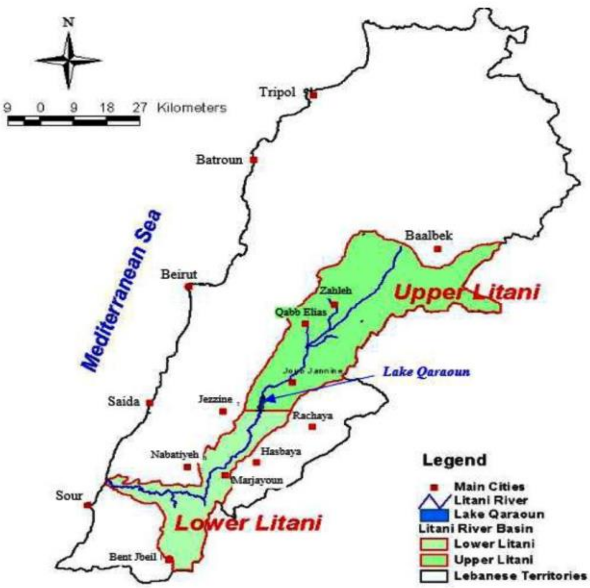

Fig. 1: The Litani River [22]

Quaroun Reservoir has three mains outputs (Fig. 2):

- The power generation tunnels which are located at an elevation of 810 m above sea level and have a total capacity of 22 m^3/s. these tunnels diverted a volume of 226×10^6 m^3. This water was used to generate energy at three hydroelectric power stations, namely, The Paul Arcache power plant located at Markabi (34 MW installed capacity), The Charles Helou power plant at Awali (108 MW installed capacity) and the Abdel-Aal power plant at Joun (48 MW).

- Two discharge towers originally used to empty the reservoir with a total capacity of 21 m^3/s, and currently used to supply Canal 900, an irrigation canal.

- The bell-mouth spillway, located near the dam at an elevation of 859 m, used to convey the overflow into the Litani River at the bottom of the dam, thereby avoiding the water overtopping, damaging or even destroying the dam.

The surplus of electricity produced by wind turbine during the night could be stored in one of these three hydraulic plants.

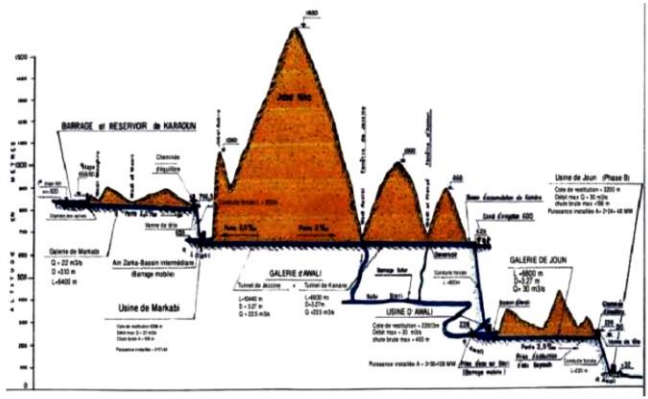

Fig. 2: Existing hydraulic power plants in Lebanon†

The kind of hydraulic turbines installed in each power plant and their upper reservoirs heights and capacities are given in **Table 2**. Awali plant has the highest production capacity, while Markabi plant has the lowest production capacity. The upper reservoir size of Markabi plant is highest while the upper reservoir size of Awali plant is lowest. It means that the largest amount of water can be stored in Markabi plant.

Table 2: Characteristics of hydraulic power plants‡in Lebanon

Power house	Turbine	Upper reservoir		
		Name	**Capacity (m^3)**	**Rate of flow (m^3/s)**
Markabi	Francis	Quaraoun	224×10^6	22
Awali	Pelton	Anane	170000	33
Joun	Francis	Awali	300000	30

-The excess of electricity produced by wind turbines

The wind turbine chosen to be installed generates 7.5 MW maximum. Figure 3 shows the calculated power curve given by the manufacturer. Based on this graph, we can evaluate the electrical power produced for each wind speed at each site.

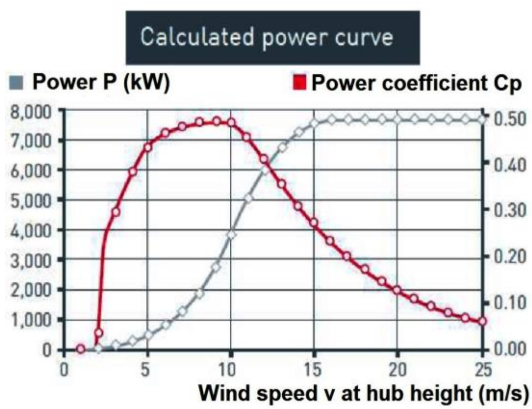

Fig. 3: Calculated power curve of the wind turbine chosen [23]

† Office National du Litani, last visit December 2014, http://www.litani.gov.lb/fr/

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The mean hourly excess of electricity for each month, produced by the 116 wind turbines that could be erected in the five selected sites, recorded at night, is given in figure 4 [17].The mean hourly excess of electricity is calculated by subtracting the mean hourly demand of electricity from the sum of the mean hourly-recorded electricity supply and the mean hourly amount of electricity that could be produced by 116 wind turbines in the five selected sites during three years (2008-2009-2010).

As can be observed in figure 4, excess is minor during the summer, due to the increased power needs in this season, but is significant during the rest of year especially during March and April. Contrariwise, no excess at all is recorded during August and September.

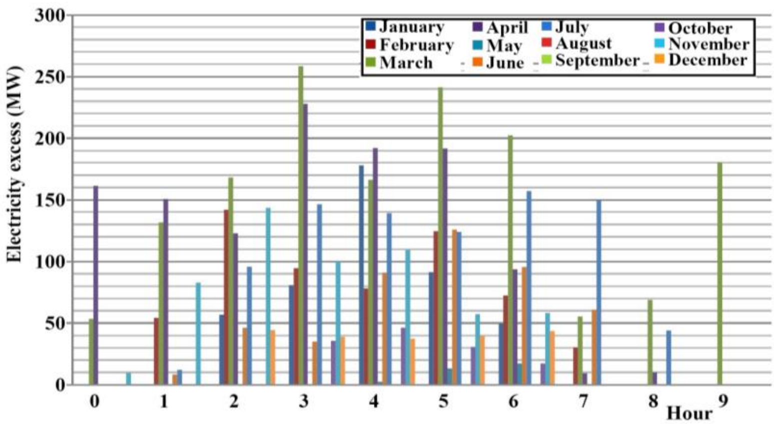


Fig. 4: Hourly excess of electricity recorded at night for each month in the five selected sites to implement wind turbines in Lebanon [17]

4. PUMPED STORAGE STATION MODEL

4.1 Description of a PHES

Hydro pump storage systems are made up of water reservoirs, hydro-turbines, hydro pumps and motors (figure 4). In this study, the water reservoirs and hydro turbines exist in the three hydraulic power plants.

In order to store the excess of electricity, we should install pumps and motors to pump water in a reservoir from a low altitude up to a reservoir at a high altitude and a lower reservoir in Joun plant.

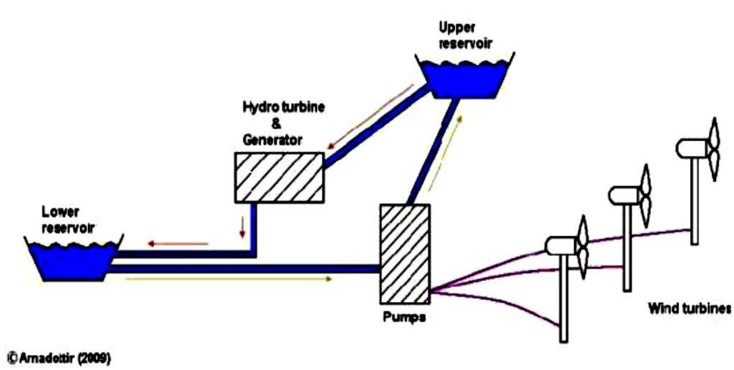


Fig. 5: A pumped storage system with wind turbines producing electricity [24]

In order to pump a water flow Q_w from the downstream reservoir to the upstream reservoir, we need pumps with an installed power of:

$$P_p = \frac{\rho_w . Q_w . g\,(H_{geo} + H_l)}{\eta_p} \quad (1)$$

Where ρ_w the water specific weight (kg/m^3), g the gravity acceleration (m/s^2), Q_w the volumetric flow rate (m^3/s), H_{geo} the difference between upper and lower reservoirs (m), H_l the head loss, η_p the pump efficiency (%).

Electric input power required to drive a pump can be calculated by the equation:

$$P_e = P_p \,/\, \eta_m \quad (2)$$

Where η_m is the motor efficiency /(%).

For the estimation of the head loss, various methods are proposed in the literature. The head loss is often given by the Darcy-Weisbach formula as:

$$H_l = \frac{L.v^2}{2\,D.g} f \quad (3)$$

Where, f, the friction factor; L, the pipe length (m), v, the water flow velocity (m/s), D, the pipe diameter (m).

Velocity of the flow in pipes can be calculated by the equation.

$$Q_w = v.\pi.\left(D/2\right)^2 \quad (4)$$

{Eq. (3)} and {Eq. (4)} provide an estimation of the head loss H_l that can be calculated as:

$$H_l = \frac{8\,f\,L}{g\,\pi^2\,D^5} Q_w^2 \quad (5)$$

4.2 Hydro-pumps selection

The Ternary group, which use independent turbines and pumps, is chosen to be installed in this study because the turbines are already exists.

Due to their durability, versatility and simplicity, centrifugal pumps are the most popular type of pumps [25]. Pump efficiency is measured by how much of the power input to the shaft is converted to useful water pumping by the pump [25]. It is therefore not fixed for a centrifugal pump because it is a function of the discharge and therefore also of the operating head and the frequency.

Typical selection criteria for centrifugal pumps are their design parameters: flow rate or capacity Q_w, discharge head $H(H_{geo} + H_l)$, speed of rotation n and NPSH (Net Positive Suction Head).

4.2.1 The required flow rate and discharge head

System characteristic curve

The system characteristic curve plots the discharge head H_{sys} required by the system as a function of the flow rate Q_w. It is composed of the so-called ‘static’ and ‘dynamic’ components (Fig. 6). The static component consists of the geodetic head H_{geo} and the pressure head difference $(P_a - P_e)/(\rho g)$ between the inlet and outlet tanks, which are independent of the flow rate. The dynamic component consists of the head loss H_I, which increases as the square of the flow rate Q_w.

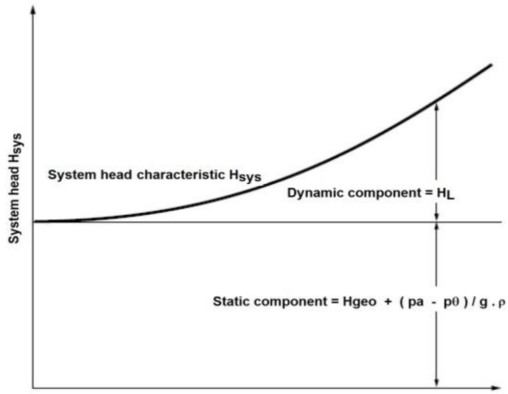


Fig. 6: System characteristic curve H_{sys} with static and dynamic components [26]

The data required for selecting a pump size, i.e. the flow rate Q_w and the discharge head H of the desired operating point are assumed to be known from the system characteristic curve; the electric main frequency is also given. With these values, it is possible to choose the pump size, the speed of rotation and, if necessary, the number of stages, from the selection chart in the sales literature. If there are no specific reasons for doing otherwise, a pump should be selected so that the operating point lies near its best efficiency point Q_{opt} (= flow rate at which pump efficiency is the highest) [26].

4.2.2 Operating point

The operating point of a centrifugal pump, also called its duty point, is given by the intersection of the pump characteristic curve with the system characteristic curve. The flow rate Q and the developed head H are both determined by the intersection. To change the operating point either the system curve or the pump curve must be changed.

For pumps operating in series (one after the other) the developed heads H_1, H_2, etc. of the individual characteristic curves must be added (after sub tracting any head losses which occur between them) to obtain the total characteristic $H = f(Q)$.

For pumps operating in parallel**,** the individual characteristics H_1, H_2, etc. $= f(Q)$ are first reduced by the head losses occurring up to the common node and plotted versus Q. Then the flow rates Q of the reduced characteristics are added to produce the effective characteristic curve of a "virtual" pump (figure 6). This characteristic interacts with the system curve H_{sys} for the rest of the system through the intersection node.

5. WATER PUMPING SYSTEM USING WIND ENERGY

The hydraulic energy, E_{he}, requires delivering a volume of water, V_w (m^3), from a height (h_1) to another height (h_2)

$$E_{he} = \frac{\rho_w . V_w . g.(H_{geo} + H_1)}{\eta_p} \quad (6)$$

where V_w, the volume of water (m^3) and $H = H_1 + H_{geo}$, head (m).

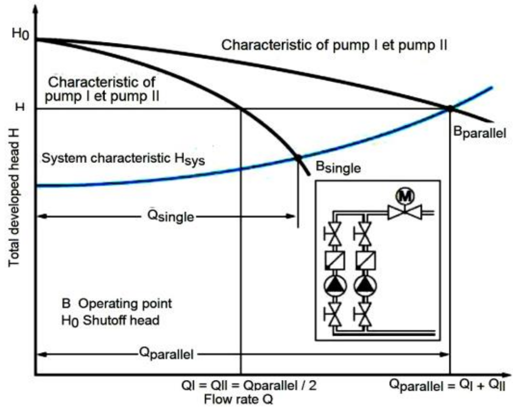


Fig. 7: Parallel operation of 2 identical centrifugal pumps with stable characteristic curves [26]

Power can be defined as

$$P_{wt} = \frac{E_{he}}{\Delta t} = \frac{\rho_w . V_w . g.(H_{geo} + H_1)}{\eta \Delta_t} \rightarrow P_{wt} = \frac{\rho_w . Q_w . g. H}{\eta} \quad (7)$$

Where, P_{wt}, the excess power of wind turbines (W) and the volumetric flow rate water $Q_w (m^3/s)$, can be expressed as

$$Q_w = \frac{\eta P_{wt}}{\rho_w . g. H} \quad (8)$$

Or the equation of the volume of water, V_w (cm^3) can be expressed,

$$V_w = \frac{\eta . E_{wt}}{\rho_w . g. H} 3600 \quad (9)$$

where, E_{wt}, is the excess energy of wind turbines (Wh).

A system can never operate at 100 % efficiency. The total efficiency of a pumping system (η) is a function of pump efficiency (η_p), transmission efficiency between the prime mover and the rotating equipment (η_t), and the efficiency of the motor (η_m).

Mathematically, this may be expressed as

$$\eta = \eta_p . \eta_t . \eta_m \quad (10)$$

6. COST ANALYSIS OF PUMPED STORAGE SYSTEM

The method of LCC is most largely used to evaluate the financial viability of a system [27, 28]. The life cycle cost of a pumping system can be calculated using the following equation:

$$LCC = C_{inv} + C_{maint} + C_{remp} \quad (11)$$

where C_{inv} includes the initial capital expenditure, design and installation of system. This cost is still considered payment occurring in the initial year of installing the system or by annuities;

C_{maint}, the maintenance cost, is the sum of all costs annually scheduled;

C_{remp}, the replacement costs, is the sum of all cost of replacing equipment provided during the life cycle of the system occurs only in specific years

Initial cost

The main constituent components of a pumping water system are:

-A controller,

-An inverter DC/AC.

-A pump unit, whose characteristics depend on those of the water source.

Maintenance cost

-Maintenance costs also some recurrent costs, are usually specified as a percentage of the cost of initial capital. All costs are subject to an annual inflation rate (i) and a discount rate (d).

-Maintenance costs are expressed by {Eq. (21)}.

$$C_{maint} = M_0 \left(\frac{1+i}{d-i} \right) \times \left(1 - \left(\frac{1+i}{d+i} \right)^{nv} \right) \text{ if } d \neq i \quad (12)$$

M_0, is the operating and maintenance cost during the first year; n_v is the life of pumping system.

Replacement costs

The replacement cost of each component of the system is mainly based on the number of substitutions on the life, its value is given by the following equation [29-31]:

$$C_{remp} = C_u \times \sum_{j=1}^{n} \left(\frac{1+i}{1+d} \right)^{\left(\frac{n_v . n}{n+1} \right)} \quad (13)$$

where C_u is the unit cost of component replacement and n is the number of replacing on the life cycle.

The following expression has been used to estimate the cost of water to be pumped per m^3,

$$C_w = \frac{LCC}{V_{wy}} . \text{cost} / m^3 \quad (14)$$

Where LCC is the life cost (%), V_{wy} is the annual volume of water pumped using the surplus of wind energy (m^3) and is determined from [32],

$$V_{wy} = \frac{\eta . E_{wt}}{\rho_w . g . H} \frac{24 \times 3600}{24 \times 365}, \text{ m}^3\text{/year} \quad (15)$$

Where E_{wt}, is hourly excess of electricity (Wh).

7. COST ANALYSIS OF WIND ENERGY

Since the economic viability of the wind energy projects depends on its ability to generate electricity at a low operating cost per unit energy, an accurate estimation of all costs occurring over the life span of the system is essential. Different methods are generally used to estimate the operating cost of a unit energy produced by the wind energy conversion system [33-35].

In this study, the estimation of the cost per unit is made by estimating the specific cost per kWh, which is expressed as the ratio of the accumulated net present value of all costs, PVC, to the total energy produced by the system during the wind turbine lifetime [36 - 38].

The determination of the unit cost of energy involves two mains steps. In the first step, the PVC is calculated by taking into consideration the initial investment cost of the system and the present value of operations and maintenance cost throughout the lifetime system. The second step consists to determine the unit cost of energy (per kWh).

7.1 The present value of costs

The present value of costs (PVC) can be calculated as follows:

$$PVC = IC + C_{omp} \tag{16}$$

Where, IC is the initial cost, C_{omp} is the present value of operation and maintenance cost during the system life.

-The initial investment cost of the wind turbine system consists of the wind turbine cost and all other initial costs including those of civil work, installation, connection cables to the grid and power conditioning.

-The cost of the wind turbine can be determined as follows:

$$C_{wt} = C_{spe} \cdot P_r \tag{17}$$

Where C_{spe} and Pr are, respectively, the specific cost and the rated power of the wind turbine.

The specific turbine cost is dependent on the rated power of the wind turbine but varies according to manufacturers [33, 34, 36]. We chose the specific turbine cost in considering three intervals (maximum and minimum values) as seen in **Table 3** [34, 36].

In this table, we note that the cost per kW decreases with the increase of the wind turbine size. For machine size above 200 kW, the turbine cost can be taken as 1150 $/kW (average value between a minimum of 700 $/kW and a maximum of 1600 $/kW).

Table 3: Range of specific cost of wind turbines based on the rated power

Wind turbine size kW	Specific cost $/kW	Average specific cost $/kW
< 20	2200-3000	2600
20-200	1250-2300	1775
>200	700-1600	1150

The other initial costs are generally expressed as a percentage of the wind turbine cost. In this study, they are assumed to be 30% of the wind turbine cost.

-The present value of operation and maintenance costs (20 years of maintenance) of the wind turbines is expressed as [34, 39]

$$C_{om(p)} = C_{omr}\left(\frac{1+i}{d-i}\right)\times\left(1-\left(\frac{1+i}{d+i}\right)^{t}\right) \tag{18}$$

Where, i, d et t are the inflation rate for operation, the interest rate and the useful lifetime of turbine in years (20 years) respectively.

C_{omr} is the operation and maintenance cost for the first year. This cost is expressed as a fraction of the component cost. In this study, it is assumed to be 25 % of the annual cost of the turbine (machine price/life time) [37, 38, 40].

7.2 The unit cost of energy

Finally, the cost per kWh of electricity generation can be determined. The following expression has been used to estimate the unit cost of energy (UCE) [41-43].

$$UCE\,(\$/kWh) = PVC \,/\, E_{wgt} \tag{19}$$

E_{wgt} is the annual energy produced by wind turbines.

8. RESULTS AND DISCUSSION

8.1 Pumps and engines selection

The specifications of the selected hydro pumps, which are used to pump water to the upper reservoir, and selected engines to drive pumps, for each studied hydraulic plants are available in **Table 4**.

The results concerning selected pumps and engines for each hydraulic plant are the following:

-**Markabi**: A system requires a flow of 39600 m^3/h and a 205.10 m system head. The required system flow and head can be handled by 8 paralleled-pumps, 7 as operating units and one as spare unit. Each pump will have a 51.8 MW drive motor. The amount of absorbed energy by pumps is 362.6 MW.

-**Awali**: A system requires a flow of 39600 m^3/h and a 459.40 m system head. The required system flow and head can be handled by 9 paralleled-pumps, 8 as operating units and one as spare unit. Each pump will have a 82.35 MW drive motor. The amount of absorbed energy by pumps is 658.8 MW.

-**Joun**: A system requires a flow of 54000 m^3/h and a 214.30 m system head. The required system flow and head can be handled by 9 paralleled-pumps, 8 as operating units and one as spare unit. Each pump will have a 52.9 MW drive motor. The amount of absorbed energy by pumps is 423.2 MW.

In the three hydraulic plants, the $NPSH_a < NPSH_r$, so there is no risk of cavitation. The pump efficiency of the three types of selected pumps is 88 %.

We notice that the highest amount of absorbed energy by pumps is recorded in Awali plant while the lowest is recorded in Markabi plant.

Based on the known flow rate at the known head for each plant, a system-head curve can be constructed using the fact that pumping head varies as the square of the change in flow, or:

$$\frac{Q_2}{Q_1} = \frac{H_2}{H_1} \tag{20}$$

where Q_1 : known design flow (m^3/h), Q_2 : selected flow (m^3/h), H_1 : know n design head (m), H_2 : resultant head related to selected flow rate (m).

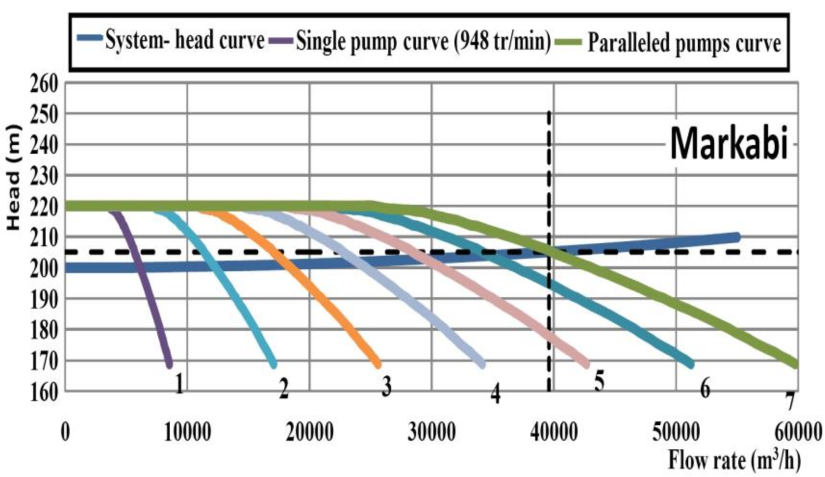
Construct the paralleled-pumps curve by multiplying the flow of a single pump by pumps number at a given head, using data from the pump manufacturer.

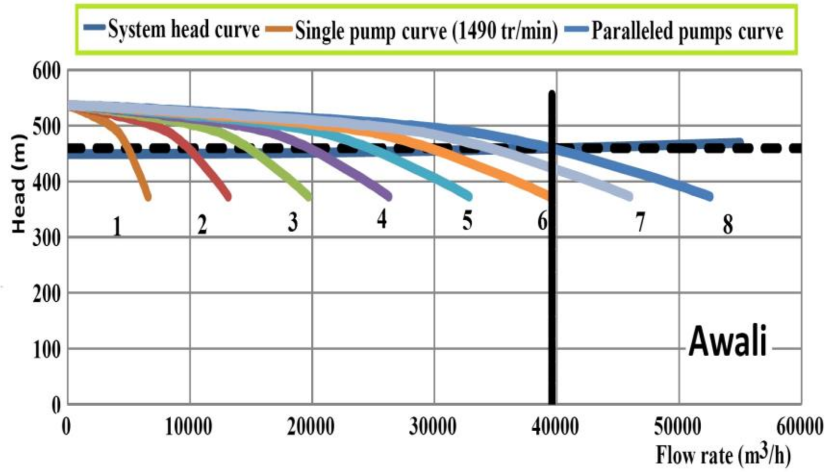
Once the system-head curve is plotted, we draw the single-pump curve of the selected pump and the paralleled-pump curve. The point of crossing of the paralleled-pumps curve with the system head curve is at the required value of flow rate and head because it was planned.

The plotted system-head curve, the single-pump curve and paralleled-pumps curve for Markabi, Awali and Joun are shown respectively in Fig. 8**a-**, Fig. 8**b-** and Fig. 8**c-**.

Table 4: Characteristics of the selected pumps and motors for each hydraulic plant

	Markabi	**Awali**	**Joun**
$Q_w\,(m^3/h)$	39600	39600	54000
$H\,(m)$	205.1	459.4	214.3
NPSHa **(mCE)**	38.96	35.96	34.96
	RLO 600-1200A	**RLO 500-1200A**	**RLO 600-1200A**
Q (m^3/h)	5657	4950	6750
H (m)	205.10	459.40	214.30
η_p (%)	88	88	88
NPSHr (mCE)	6.20	22	6.3
Nb of pumps	7+1	8+1	8+1
Power absorbed by each pump (MW)	4.7	8.2	5.29
Power absorbed by pump (MW)	32.9	65.6	42.3
Power absorbed by motors (MW)	38.7	77.1	49.8
Motors characteristics	-6kV IP54classe F -Rotation speed: 1500 tr/min Use in speed variation	-6kV IP54classe F -Rotation speed: 1500 tr/min Use in speed variation	-6kV IP54classe F -Rotation speed: 1500 tr/min Use in speed variation





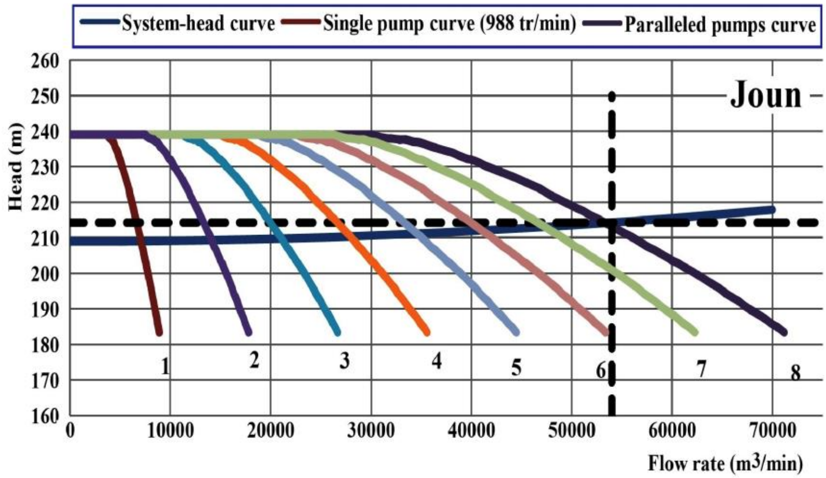


Fig. 8: The plotted system-head curve, the single-pump curve and paralleled-pumps curve for Markabi (**a-**), Awali (**b-**) and Joun (**c-**)

8.2 The most suitable hydraulic plant to store the excess of wind energy

In order to choose the most suitable hydraulic plant to store the excess of electricity produced by the wind turbines, an economic analysis of the water pumping system. In addition, a comparison between the amount of water that could be pumped with the excess of electricity, the absorbed energy by pumps and the upper reservoir size in each hydraulic plant should be made.

8.2.1 Analysis of the amount of pumped water

Figure 9 shows the hourly amount of water that could be pumped with the excess of wind turbine energy during night at each of the three studied hydraulic plants, using (08) motor-pump units in Markabi, (09) motor-pump units in Awali and (09) motor-pump units in Joun.

In the three hydraulic plants, we can not pump water in September and August.

As we can see in figure 9, water-pumping capacity is high during March, April and July. This is due to the high wind speed available during these months. The highest hourly amount of water that could be pumped in Markabi is 263000 m^3 (Fig. 9**a-**), in Awali is 117000 m^3 (Fig. 9**b-**) and in Joun is 252000 m^3 (Fig. 9**c-**).

We notice that the highest amount of water that could be pumped in the three hydraulic plants is recorded in March at 03:00 am.

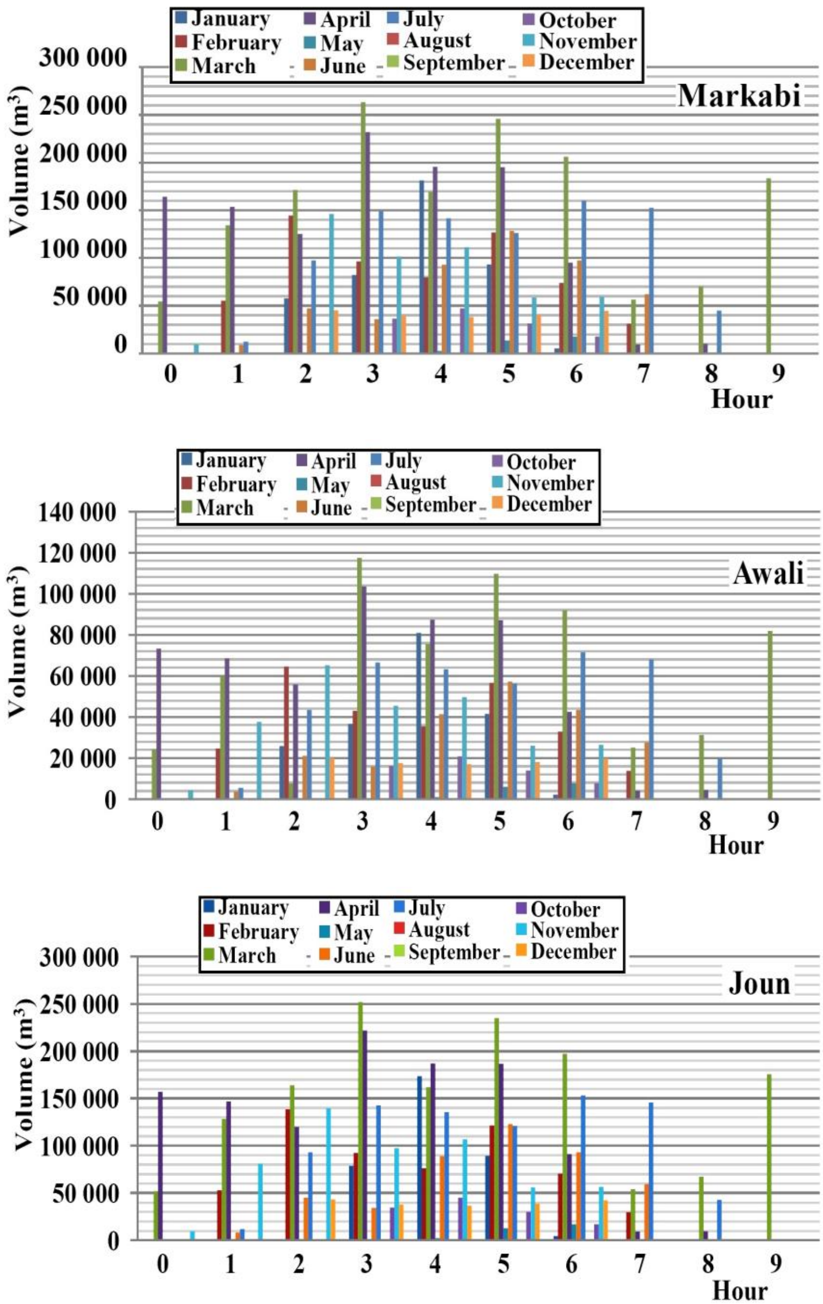


Fig. 9: Hourly pumped volume of water at night (between Midnight and 9:00 am) in Markabi **a-**, Awali **b-** and Joun **c-**

The total daily amount of water that could be pumped with the excess of electricity produced by the wind turbines at night in each studied hydraulic plant and for each month is shown in figure 10. The range of water pumping capacity varies from 0 to 1553967 m^3 per day in August and September (in the three hydraulic plants) and March (in Markabi) for the minimum and maximum values respectively. The highest amount of daily water that could be pumped for all months is in Markabi, while, the lowest amount of daily water that could be pumped for all months is in Awali.

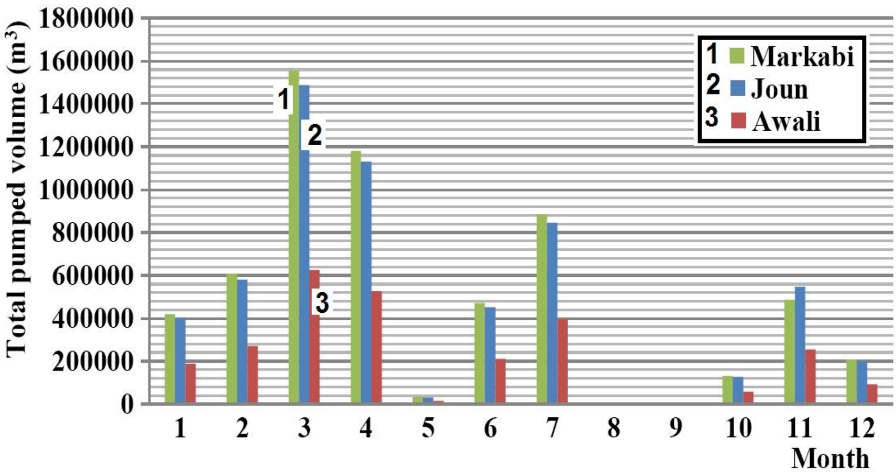


Fig. 10: Total monthly volume pumped of water in each hydraulic plant

8.2.2 Analysis of absorbed power by pumps

The requested amount of absorbed power by pumps in each hydraulic plant and the amount of daily excess power of electricity are shown in figure 11. We notice that the requested absorbed power by pumps could be covered by the daily excess of electricity in Awali and Joun during all months except May, August and September. While, it could be covered during all months except during August and September (no excess during this two months) in Joun and in Markabi.

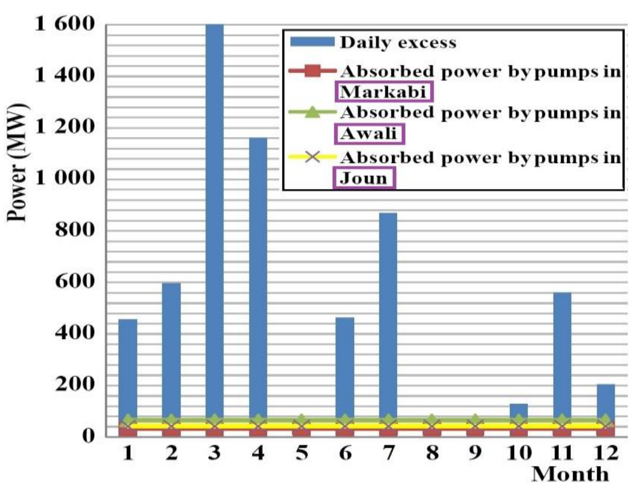


Fig. 11: The daily excess power and the requested Absorbed power by pumps in each studied plants

8.2.3 Analysis of evacuated volume

The amount of water volume that could be stored in the upper reservoir, the amount of water volume that could be evacuated and the evacuation time in each hydraulic plant are shown in **Tables 5**, **6**, **7**. We notice that the capacities of the upper tanks in Awali and Joun are smaller than the volume of water that could be pumped in all months except May, October and December.

Hence, the amount of pumped water could not be stored completely in Awali and Joun in all months except May, October and December; the upper tank should be bigger.

Contrariwise, the capacity of the upper tank in Markabi is greater than the volume of water that could be pumped in all months. Hence, the amount of pumped water could be stored completely in Markabi.

Table 5: Daily evacuated of water and time of evacuation in **Awali**

	Jan.	Feb.	March	April	May	June
V (m^3/day)	187.321	271.067	624.985	527.036	14.985	210.545
V reservoir (m^3)	170000	170000	170000	170000	170000	170000
Rate of flow(m^3/s)	33	33	33	33	33	33
Evacuated volume (m^3)	170000	170000	170000	170000	14.985	170000
Time of evacuation (min)	85.86	85.86	85.86	85.86	7.57	85.86
	July	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
V (m^3/day)	394.661	0	0	59.027	254.928	92.674
V reservoir (m^3)	17000	0	0	59.027	170000	92.674
Rate of flow(m^3/s)	33	33	33	33	33	33
Evacuated volume (m^3)	170000	0	0	59.027	170000	92.674
Time of evacuation (min)	85.86	0.00	0.00	29.81	85.86	46.80

Table 6: Daily evacuated of water and time of evacuation in **Joun**

	Jan.	Feb.	March	April	May	June
V (m^3/day)	346.210	581.093	1.487.254	1.129.819	32.124	451.351
V reservoir (m^3)	300000	300000	300000	300000	300000	300000
Rate of flow(m^3/s)	30	30	30	30	30	30
Evacuated volume (m^3)	300000	300000	300000	300000	32.124	300000
Time of evacuation (min)	166.67	166.67	166.67	166.67	17.85	166.67
	July	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
V (m^3/day)	846.044	0	0	126.537	546.495	198.667
V reservoir (m^3)	300000	300000	300000	300000	300000	300000
Rate of flow(m^3/s)	30	30	30	30	30	30
Evacuated volume (m^3)	300000	0	0	126.537	1300000	198.667
Time of evacuation (min)	166.67	0.00	0.00	70.30	166.67	110.37

Table 7: Daily evacuated of water and time of evacuation in **Markabi**

	Jan.	Feb.	March	April	May	June
V (m^3/day)	419.578	607.159	1.553.967	1.180.499	33.565	471.597
V reservoir (m^3)	224000	224000	224000	224000	224000	224000
Rate of flow(m^3/s)	22	22	22	22	22	22
Evacuated volume (m^3)	419.578	607.159	1.553.967	1.180.499	33.565	471.597
Time of evacuation (min)	166.67	166.67	166.67	166.67	17.85	166.67
	July	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
V (m^3/day)	883.995	0	0	132.213	486.809	207.578
V reservoir (m^3)	224000	224000	224000	224000	224000	224000
Rate of flow(m^3/s)	22	22	22	22	22	22
Evacuated volume (m^3)	883.995	0	0	132.213	486.809	207.578
Time of evacuation (min)	669.69	0.00	0.00	100.16	368.79	157.26

8.2.4 Economic analysis of water pumping system using wind turbine energy

The input parameters used for the economic evaluation are the estimated cost of various components of the systems, interest and inflation rates, the lifetime of pumping system, costs of maintenance and operation and replacement cost of some subset. The analysis period is assumed to be 20 years at an interest rate of 5.7 % and inflation rate of 4.7 %. The cost of system installation of the motor-pump is assumed to be equal 3 % of the total cost of equipment [44]. The maintenance and operation cost during the first year is equal to 1 % of the total cost of equipment [44]. The motor-pump units are replaced after a period of 10 years.

The cost analysis of water delivered by the water pumping system using the excess of electricity produced by wind turbines at Markabi, Awali and Joun is given in **Table 8**. The cost of water delivered is found to vary from 0.0056 US¢ per cubic meter in Markabi plant to 0.0180 US¢ per cubic meters in Awali plant. Based on the assumptions used in this analysis, the installing of water pumping system is most economically viable in Markabi.

Table 8: Cost of water pumping at the three studied hydraulic plants

	Cost of pump Motor unit($)	**LCC ($)**	**Annualy volume of Pumping water (m^3)**	**Costs of m^3 water produced ($/$m^3$)**
Markabi	8.520	19.263	341.474.680.00	0.000056
Awali	19.164	43.328	241.282.770.00	0.000180
Joun	12.298	27.805	338.616.155.00	0.000082

8.3 Cost analysis for wind energy

The economic analysis was carried out to estimate the cost of the kWh of energy produced by the selected wind turbines. The cost estimation has been done under the following assumptions [36, 40]:

- The operation, maintenance and repair cost (C_{om}) was considered to be 25% of the annual cost of the wind turbine (machine price/lifetime);
- The interest rate (d) and inflation rate (i) were taken to be 5.7 % and 4.7 %, respectively;
- The wind turbine lifetime (t) was assumed to be 20 years. Actually, based on the experience gained over the past 15 years, the wind turbine lifetime is certainly more than 20 years and could be estimated at 40 years;
- The other initial costs including the costs of civil work, installation, connection cables to the grid and power conditioning are assumed to be 30 % of the wind turbine cost.

The results of the cost analysis are presented in **Table 9**. We found that,

PVC =14.178.981.420 $

Table 9: Cost analysis for each site

Site	V_m (hub height)(m/s)	Rated power (kW)	C_f	E_{wgt} (kWh/year)	E_{wgt} (kWh/ 20 years)	UCE ($/kWh)
Marjyoun	9.16	7500	0.480	29959200	599184000	0,0193
Klaiaat	8.83	7500	0.476	29709540	594190800	0,0195
Cedars	7.79	7500	0.472	29459880	589197600	0,0196
Daher-el Baydar	11.48	7500	0.480	29959200	599184000	0,0193
Quaraoun	8.14	7500	0.466	29085390	581707800	0,0199

It can be observed in **Table 9** that the two sites that, Cedars and Daher El Baydar, have the values extreme of wind speed produce approximately the same amount of electricity (less than 500,000 kWh of annual difference). This little difference could be explained by the fact that the wind speed is regular in Cedars but it is not regular in Daher El Baydar.

According to the cost analysis, it is seen that the cost of electricity per kWh produced using the selected wind turbine varies between a minimum of 0.0193 $/kWh at Daher El Baydar and Marjyoun and a maximum of 0.0199 $/kWh at Quaraoun. Lebanon produces electricity at a much higher average of 0.078 $/kWh [45].

Moreover, it can be inferred that the unit energy cost depends on the site; thus, the average cost per kW h in Quaraoun is about three times higher than in Daher El Baydar.

The cost of electricity per kWh produced is lower than the cost of purchase price of this electricity, since the cost of purchase can not only repay the construction costs, service and maintenance, but to remunerate the capital invested.

According to the characteristics of the site, particularly the intensity of the wind, the purchase price will be between 67 €/MWh during the first fifteen years for a very good site (85 €/MWh during ten years and 29 €/MWh during five years) and 85 €/MWh during fifteen years for a mediocre site (updated values for 2013)[§].Then the market-selling price will be around 50 €/MWh for the rest of the lifetime of the wind turbine, which is at least twenty years[3].

In order to estimate the purchase price of electricity produced by wind turbine in Lebanon, the prices indicated above could be used.

The important result derived from the current study encourages the construction of wind farms in Lebanon especially of Daher El Baydar and Marjyoun for electricity generation. In addition, the usage of the selected wind turbine is highly recommended.

9. CONCLUSION

This study presents a system that aims to supply energy demand to Lebanon based on both regional energy load, wind energy potential and hydro-pumped system. A wind power system is used together with a hydro-pump storage system. Furthermore, this study is the first application of wind-hydro pumped storage system in Lebanon and this system works efficiently to cover a significant amount of electricity demand in Lebanon. Following major points have been noticed in the present work:

- The total monthly amount of water that could be pumped with the excess of electricity varies between 0 and 1553967 m^3 per day in August and September (in the three hydraulic plants) and in March (in Markabi) for the minimum and maximum values respectively.

- The cost of water delivered is found to vary from 0.0056 US¢ per cubic meter in Markabi plant to 0.0180 US¢ per cubic meters in Awali plant. The installation of water pumping system is most suitable in Markabi hydraulic plant, because:

- The highest amount of water that could be pumped is recorded in Markabi;
- The lowest absorbed energy by pumps is recorded in Markabi plant;
- Markabi has the highest upper reservoir size;

[§] Site web: http://energeia.voila.net/electri/cout_electri.htm, last visited 18/05/15.

- The total amount of water pumped volume could be stored in the upper tank in Markabi, but it could not stored nor in the upper tank in Awali nor Joun;
- The installing of water pumping system is most economically in Markabi.

- The cost of electricity per kWh produced by wind turbines that could be erected in five selected sites in Lebanon vary between 0.052 $/kWh in Daher El Baydar and 0.144 $/kWh in Quaraoun. We encourage the construction of wind farms in Lebanon completed with hydro storage.

- This study confirms the results that show the importance of using renewable energy (wind power) to improve the sustainability of the Lebanese electricity system [19-21].

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