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Theoretical Study of Producing Sustainable Electrical Energy via Hydraulic Energy

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Abstract

Over the last decade, the Libyan National Power Grid has significantly suffered from negligence and vandalisms, which led to severe materialistic damage to power generation units, transmission networks, distribution subsystems and power plants fuel shortage. These happen because of the security incidents and armed clashes within the country. This has placed the electrical power grid in a difficult and critical situation leading to a large deficit in meeting the demand for electricity use, therefore consequence to power cuts for long time.

However, the Libyan Man-Made River LMMR is considered as the world largest irrigation project, consisting of a large network of pipes that supplies water from Libyan Desert in the south to the coastal areas in the north. This water movement crossing mountains and various land orientations from the south to the north of the country has a huge kinetic energy as a result.

This paper is examined the possibility of taking advantage of the water flow energy through the Libyan western mountains to generate energy (producing electricity through water movement) by using an appropriate size of turbine. The work has been theoretically undertaken the opportunity of producing a clean and relatively cheap energy in the area of Abuzian near Tarhuna city. Moreover, the research is based-on realistic currently available data in term of the water flow-rate, the pipe diameter, the area orientations, and the pipeline slopes as well as the dimensions of the existing reservoirs. In summary, this research on the proposed area has suggested the required designs and calculations for selecting a turbine and an appropriate generator. As a result, the research has showed promising potential of producing 39.5 MW of the turbine power output and a net electrical producing energy of 29 MW and the generator overall efficiency is 73% through this area in the west of Libya.

Keywords: *Libyan Man-Made River (LMMR); sustainable development; renewable energy; Hydro-kinetic;*

1. Introduction and Background

The Libyan Man-Made River (LMMR) is a network of pipes that supplies water from the Sahara Desert in the south of Libya to the northern regions for using it in irrigation and domestic purposes. It is considered as the world's largest irrigation project. It consists of more than 1,300 wells, more than 500 m deep in the source regions, and supplies 6,500,000 m^3 of fresh water per day to the cities on the cost. The project's construction was divided into four essential phases [1].

As part of the LMMR project huge concrete reservoirs were constructed in various parts of the country; Some of which supply water to the various lines used to regulate and provide on demand potable water, while other reservoirs were constructed in circular open lakes, which are more than one km in diameter, for agricultural purposes.

In fact, it is about 70% of the water conveyed by the project intended for agricultural purposes, while the remaining amount is for domestic consumption throughout the year. The main reservoirs are include the following:

- Ajdabiya Reservoir (storage: 4 million cubic meters)
- Omar El-Mokhtar Grand Reservoir (storage: 24 million cubic meters)
- Omar Elmokhtar reservoir (storage: 4.7 million cubic meters)
- Ghordabiya Reservoir (storage: 6.8 million cubic meters)
- Ghordabiya Grand Reservoir (storage: 15.4 million cubic meters)
- Abuzian Reservoir (storage:300,000 m^3 daily online storage)[2]

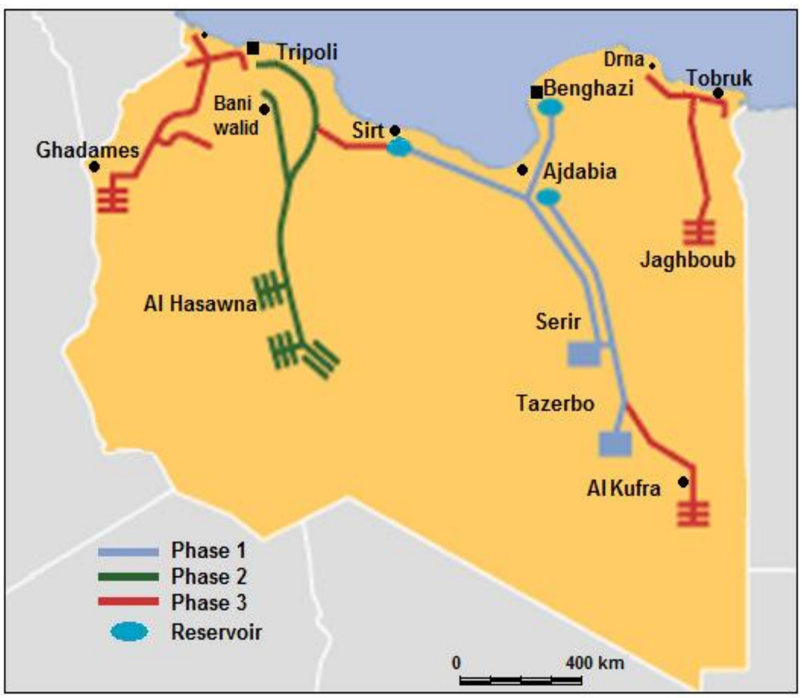


Figure 1. Libyan Man-Made River (LMMR) stages and reservoirs [4]

2. Research Geographic Area and Orientation

2.1 Tarhunah-Abu Ziyyan Orientation

The Tarhunah-Abu Ziyyan Project is designed to supply 800,000 thousand cubic meters of water per day from the regulating tank at Tarhunah to the 300,000 m3 concrete Abu Ziyyan storage reservoir. The Project includes conveyance of 1.2m to 2.8m diameter pre-stressed concrete cylinder pipe (PCCP) with an overall length of 106 km terminating in a steel pipeline connection rise of 500m to the top of the escarpment. There are also two pump stations, break pressure tank and 6 major turnouts [3].

2.2 Abu Ziyyan ReservoirDesign Specifications

As a part of area interest, based on the elevation of the Abozian reservoir, the surface of the earth to the highest point in the reservoir (500 m) and based on the topography of the mountain, the site of the turban was selected (724m) horizontally from the reservoir.

The length of the pipe was determined from the reservoir to the site of the turban (880 m) and (55 degrees) [5].

3. Turbine and Generator Design

Basically, the fundamentals of water power remain the same. Water flows across the turbine, turning a shaft connected to a generator that produces electricity. Nowadays, hydro power is mostly used to generate electrical energy on large scale by collecting water in large reservoirs or dams and it is called hydroelectric power. Turbines placed on the path of the flowing water extract its kinetic energy and convert it to mechanical energy causing the turbines to rotate at high speed. It drives a generator that converts the mechanical energy into electrical energy [6, 7].

3.1 Pelton Turbine Design Specification

This involves the calculations and measuring the net head and the water flow rate. [8]

The Net Head or the Effective Head (H_e)

$$H_e = H_g - H_i$$

Where:

H_g: is the gross head that is the vertical distance between water surface level at the intake and at the turbine (m) and this is estimated to be 500 m from the ground level in the selected area.

H_i: is the total head loss during the transit of water from the headrace to tailrace, which is mainly head loss due to friction, and is given by:

$$H_i = f * \frac{L}{D} * \frac{V^2}{2g}$$

Where:

f: is the coefficient of friction of penstock depending on the type of material of penstock.

L: is the total length of penstock = 880m

D: is the diameter of penstock and = 1.2m

$V(\frac{m}{s})$: is the mean flow velocity of water through the penstock and is calculated as:

$$V = \frac{Q}{A}$$

The flow rate (Q) = 9.25 m^3/s

The diameter area of pipe

$$A = \frac{\pi}{4} D^2 = \frac{3.14}{4} 12^2 = 1.1304\, m^2$$

Then the flow velocity of water through the penstock:

$$V = \frac{Q}{A} = \frac{9.25}{1.1304} = 8.18 \frac{m}{s}$$

To calculate the coefficient of friction of penstock f_c, the Reynolds number need to be calculated as the follow:

Reynolds Number (Re)

The dimensionless Reynolds number plays a prominent role in foreseeing the patterns in a fluid's behaviour. The Reynolds number, referred to as Re, is used to determine whether the fluid flow is laminar or turbulent. It is one of the main controlling parameters in all viscous flows where a numerical model is selected according to pre-calculated Reynolds number:

$$Re = \frac{\rho * V * D}{\mu}$$

$$Re = \frac{998 \times 8.18 \times 1.2}{1.01 * 10^{-3}} = 9.6 \times 10^6$$

Relative Roughness (RR)

The quantity used to measure the roughness of the pipe's inner surface is called the relative roughness, and it is equal to the average height of surface irregularities (ε) divided by the pipe diameter (D).

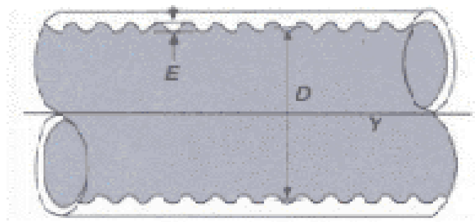


Figure 2. Relative Roughness in a Pipe

$$RR = \frac{\varepsilon}{\mathrm{D}}$$

Where both the average height surface irregularities and the pipe diameter are in millimeters:

$$RR = \frac{3\times10^{-4}}{1.2} = 0.00025$$

If we know the relative roughness of the pipe's inner surface, then we can obtain the value of the friction factor from the Moody Chart.

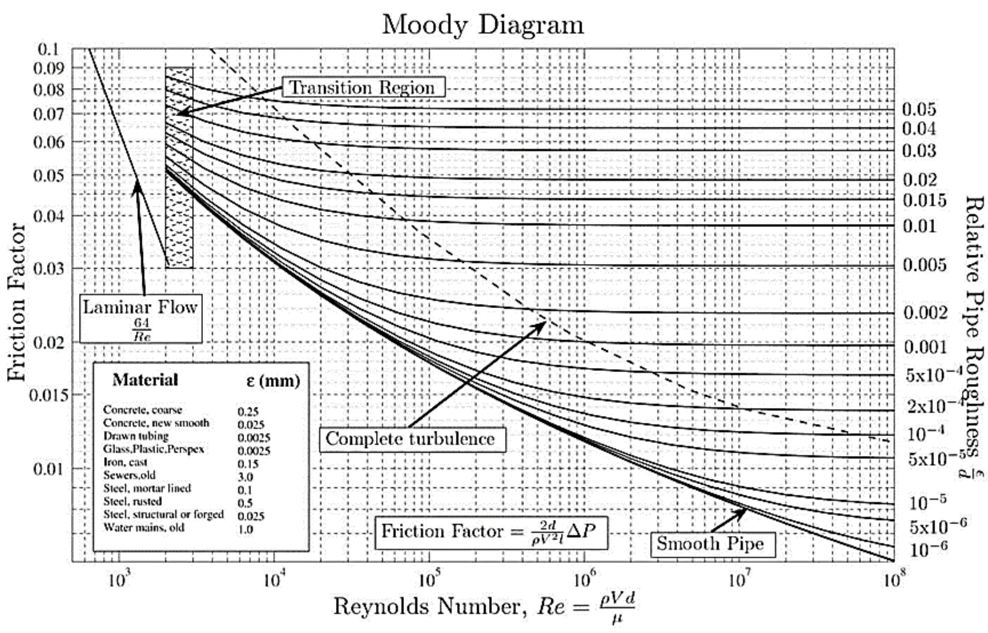


Figure 3. Moody Chart

The Moody chart (also known as the Moody diagram) is a graph in non-dimensional form that relates the Darcy friction factor, Reynolds number, and the relative roughness for fully developed flow in a circular pipe, as follow:[9]

Table 1. Absolute Roughness for Different Materials

Material	Absolut Roughness(mm)
Copper, Lead, Brass, and Aluminum	**0.001-0.002**
PVC and plastic pipes	**0.0015-0.007**
Weld steel	**0.045**
Carbon steel	**0.02-0.05**
New cast iron	**0.1-1**
Wood stave	**0.25-1**
Smoothed cement	**0.3**
Ordinary concrete	**0.3-1**
Concrete Rough from marks	**0.8-3**

The friction factor the value f_c = 0.015, so that the head loss is

$$\mathrm{H_i} = f_c * \frac{L}{D} * \frac{V^2}{2g} = \frac{0.015 * 880 * 8.18^2}{1.2 * 2 * 9.81} = 37.5\ m$$

So, the effective head (H_e) can be obtained as:

$$\mathrm{H_e} = \mathrm{H_g} - \mathrm{H_i} = 500 - 37.5 = 462 \text{ m}$$

Turbine Input Power (P_{ti})

The hydraulic input Power to the turbine in (Watt) can be calculated as:

$$\mathrm{P_{ti}} = \rho * g * C^2{}_n * \mathrm{H_e} * Q$$

C_n nozzle (jet) discharge coefficient ≈ 0.98

$$\mathrm{P_{ti}} = 998 * 9.81 * 0.98^2{}_n * 462 * 9.25 = 40\ MW$$

Specific Speed (Ω_s)

However, the calculation of the specific speed, the shaft speed is required. Since hydraulic turbines are used for electricity generation, the shaft speed must be synchronous with the frequency of the electric current.

With some exceptions the frequency is 50 Hz in Europe and Asia and 60 Hz in North and South America. To obtain the proper value for the line frequency, the shaft speed is:

$$N = \frac{120\,f}{2P}$$

Assume the number of poles on generator (P = 5)

$$N = \frac{120 \times 50}{2 \times 5} = 600\, rpm$$

Specific speed (Ω_s)

$$\Omega_s = \frac{\omega \times \sqrt{Q}}{(g \times H_e)^{\frac{3}{4}}}$$

$$\omega = \frac{2\pi \times N}{60} = 62.8\, rad/s$$

$$\Omega_s = \frac{62.8 \times \sqrt{9.25}}{(9.81 \times 462_e)^{\frac{3}{4}}} = 0.34$$

Table 2. Power Specific Speed Ranges of Hydraulic Turbines

Type	Ω_s	η%
Single jet	0.02 - 0.18	88-90
Twin jet	0.09 - 0.26	89-92
Three jet	0.10 - 0.30	89-92
Four jet	0.12 - 0.36	86

The recommended number of jets (n) is the value of 4.
Hence the discharge from each jet is:

$$Q = \frac{Q}{n} = 2.31\, m^3/s$$

Ideal velocity of the jet from the nozzle:

$$V_2 = \sqrt{2 \times g \times H_e}$$

And actual velocity of jet:

$$V_2 = C_n \sqrt{2 \times g \times H_e} = 0.98\sqrt{2 \times 9.81 \times 462}$$

$$V_2 = 93.30\ m/s$$

C_n coefficient of the velocity for nozzle is in the range of 0.97 to 0.99
The diameter of the jet:

$$d_{jet} = \sqrt{\frac{4 \times Q}{n \times \pi \times V_1}}$$

$$d_{jet} = \sqrt{\frac{4 \times 9.25}{4 \times 3.14 \times 93.30}}$$

$$d_{jet} = 0.17\ m$$

And the blade speed (U) is:

$$U = 0.45 \times V1 = 42\ m/s$$

Therefore the diameter of the wheel (D_w) is:

$$D_w = \frac{2 \times U}{\omega} = \frac{2 \times 42}{62.8} = 1.33m$$

And the number of buckets is:

$$Z = \frac{D_w}{2 \times d_{jet}} + 15 = \frac{133}{2 \times 17} + 15 = 18.9 \cong 19$$

Clearance between the nozzle and buckets is:

$$X_{nb} = 0.625 D_w = 0.83\ m$$

Bucket Dimensions

The bucket axial width can be calculated as:

$$B_w = 3d_{jet} = 0.51m$$

The bucket radial length can be calculated as:

$$B_t = 2d_{jet} = 0.34\ m$$

The bucket depth can be calculated as:

$$B_d = 0.8d_{jet} = 0.13\ m$$

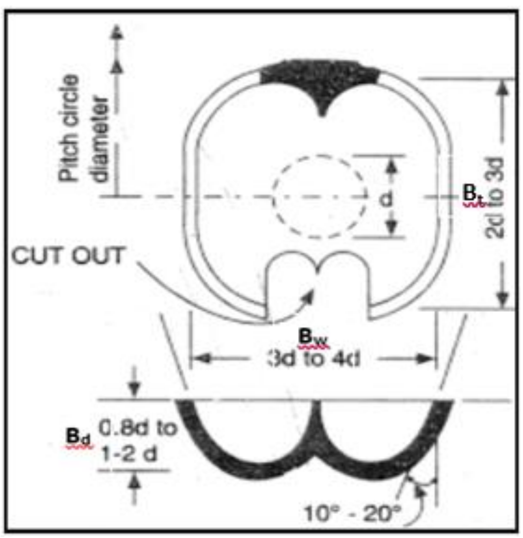


Figure 4. Bucket Dimensions

The bucket volume was given as:

$$V_b = 0.0063 D_w^3 = 0.014 m^3$$

3.2 Force, Power and Efficiency of a Pelton Wheel

The inlet and outlet velocity triangles for Pelton wheel turbine is as shown in figure below. As the runner diameter is same at inlet and outlet, tangential velocity of wheel remains the same. In practical case the relative at the outlet is slightly less than that at inlet due to frictional loss over the inner surface of the bucket.

Some velocity is also lost due to the jet striking over the splitter.

Hence:

$$W_3 = C_b W_2$$

Where C_b is bucket velocity coefficient.

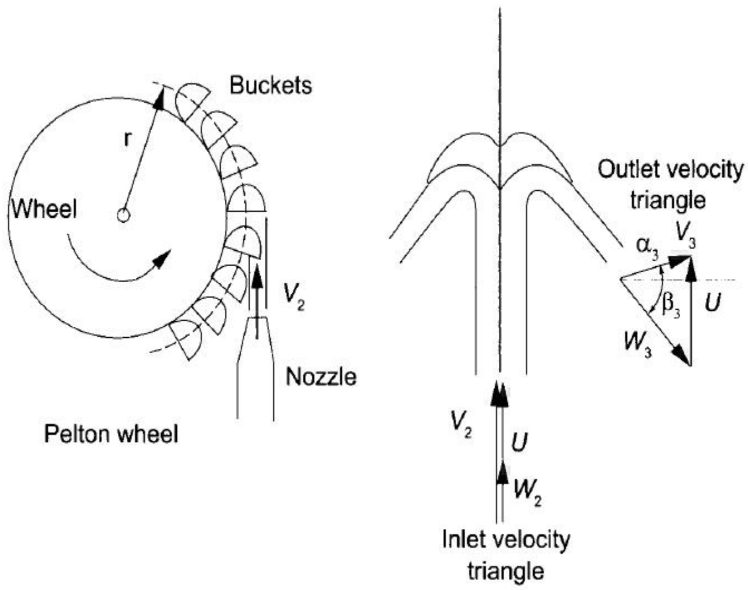


Figure 5. Velocity Triangles for Pelton Wheel Turbine

From inlet velocity triangle,

$$V_2 = V_{u2}$$
$$W_2 = V_2 - U$$

From outlet velocity triangle,

$$W_3 = C_b W_2$$

$$V_{u3} = \mathrm{U} + W_3 sin\beta_3 = \mathrm{U} + C_b W_2 sin\beta_3$$

The work done by Pelton wheel jets is:

$$\mathrm{w} = \mathrm{U}(V_{u2} - V_{u3})$$

Substituting:

$$W_2 = V_2 - U \text{ , gives}$$
$$\mathrm{w} = \mathrm{U}\ (V_2 - U)\ (1 - C_b sin\beta_3)$$

Power output by the wheel is,

$$P_H = \rho Q U(V_2 - U)(1 - C_b sin\beta_3)$$
$$P_H = 1000 * 9.25 * 42(93.3 - 42)(1 - 0.98 * \sin(-90))$$
$$P_H = 39.5\ \mathrm{MW}$$

3.3 Generator Design

If the speed is slow, the numbers of poles is high. The overall power (s) in (kV.A) is calculated as: [10]

$$s = \sqrt{3} * I * V$$

While the active power (p):

$$P = \sqrt{3} * I * V * \cos\alpha$$

Where:
α is cablence factor
While the reactive power (p):

$$\emptyset = \sqrt{3} * I * V * \sin\alpha$$

The regulated voltage applied in Hydropower are: (0.38, 6.5, 10.5, and 11) kV for 50Hz. In most countries the generators in water stations are made to work on voltage between (10.5 to 15 kV) and on the current between (250 to 1500 A).
For the resistances for stator and rotor are as follow:

$$R_S = 0.012 \quad : \quad 0.5\ \Omega$$
$$R_r = 0.03 \quad : \quad 0.5\ \Omega$$

The efficiency factor for big machines is between (0.97-0.98) and for small machines is 0.95.
The cooling-system is applied using either air-water or water-solvent or water- Hydrogen systems.
For the generator which runs in the water stations:
T = 605 KN.m, P_{out} = 39.5 MW, N = 600 rpm, Power factor = 0.8, Nominal Voltage (Vn) = 10.5 Kv Nominal Current (In) = 2 KA and Rs (Stator Resistance) = 0.01 Ω

$$s = \sqrt{3} * I * V$$

$$s = \sqrt{3} * 2 * 10.5 = 36.33MVA$$

The generator is selected on (SW36.33/10.5), and has the following specification:
Xq = 0, Xd = 0.5, and R = 0.0012 Ω.
The copper losses of stator (P_{cu}) are:
P_{cu} = I2*R = (2000)2 (0.0012) = 0.048 MW
P stray losses + P_{mech}+ P_{core} = 1.1 MW

Assume that:

$\sum$ P_{cu} + $P_{stray\ losses}$ + P_{mech}+ P_{core} = 0.048+ 1.1 = 1.148 MW
P out = S * cos α = 29.06 MW
P_{in} = P_{out} + $\sum$
P_{in} = 29.06 + 1.148 = 30.208 MW

The copper losses of rotor will be neglected because the rotor is supplied by another DC source. Therefore, the efficiency is:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{29.06}{30.208} = 0.96$$

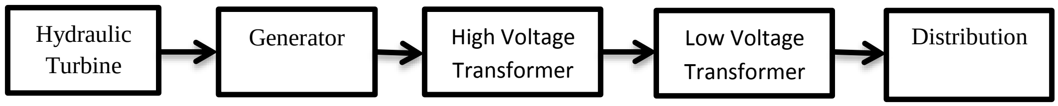
Then the appropriate power transformer can be selected as the following:
The power lines that connected to the generator must be equal to power of generator, so it can be selected from table below and they have their own technical specification. The calculation data of transmissions line (35-110) KV for 100 Km.

Table 3. The Generator Specifications

Cross section Area(mm^2)	R0,0M, +20 0C	35Kv	110Kv		
		X0,om	X0,OM	B0,10 cm	q0,mvar
AC70/11	42.8	43.2	44.4	2.55	3.40
AC95/16	30.6	42.1	43.4	2.61	3.50
AC120/19	24.9	41.4	42.7	2.66	3.55
AC150/24	19.8	40.6	42.0	2.70	3.60
AC185/29	16.2	-	41.3	2.75	3.70
AC240/32	12.0	-	40.5	2.81	3.75

The working transform that has been selected is to transfer the voltage from 10.5 to 35 KV and the transport lines cross section area = 240/32 and has the following specifications:

Ro = 12 Ω /100 km
Xo = 40 Ω /100 km



Generate 29 MW   10.5kV to 35 kV

Transport line Resistance for distance (1 km)

$$Ro = {}^{12}/_{100} = 12\ {}^{\Omega}/_{\mathrm{km}}$$

The power in both sides of transporter must be equal

$$P_1 = P_2$$
$$I_1 * V_1 = I_2 * V_2$$
$$2\mathrm{KA} * 10.5\mathrm{KV} = \mathbf{I_2} * 35\mathrm{KV}$$
$$I_2 = (2KA * {}^{10.5\mathrm{KV}}/_{35\mathrm{KV}}) = 0.6KA$$

Calculation of consumed power in line:

$$P = I^2 * R$$
$$P = (0.6KA)^2 * 0.12\ {}^{\Omega}/_{\mathrm{km}} = 43.2KW$$

Multiply in 3 to find three phases:

$$3 * 43.2KW = 129.6KW$$

The net power at the pump station is:

$$29000KW - 129.6KW = 28870.4KW$$

The efficiency of power plant is:

$$\eta = \frac{P_E}{P_H} + \frac{29}{39.5} = 73\%$$

4. Conclusions

LMMR is considered as the world's largest project that transports drinking water from the Sahara in the south to the coastal cities and villages in north of Libya; this natural water movement toward the north has the potential energy to produce a clean, safe, sustainable and renewable energy.
This paper has examined the possibility of utilizing water kinetic energy and showed the great potential of producing an electrical energy through the area of Abu Ziyyan Mountain in the west of the country. As a result, based on the theoretical method supported with real data (water flow-rate, land orientation, pipes and reservoirs geometries), this research has showed the massive chance of producing 39.5 MW of the turbine power output and a net electrical producing energy of 29 MW and the generator overall efficiency is 73% through this area in the west of Libya.

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