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Hydroelectric Pumping Station at King Talal Dam

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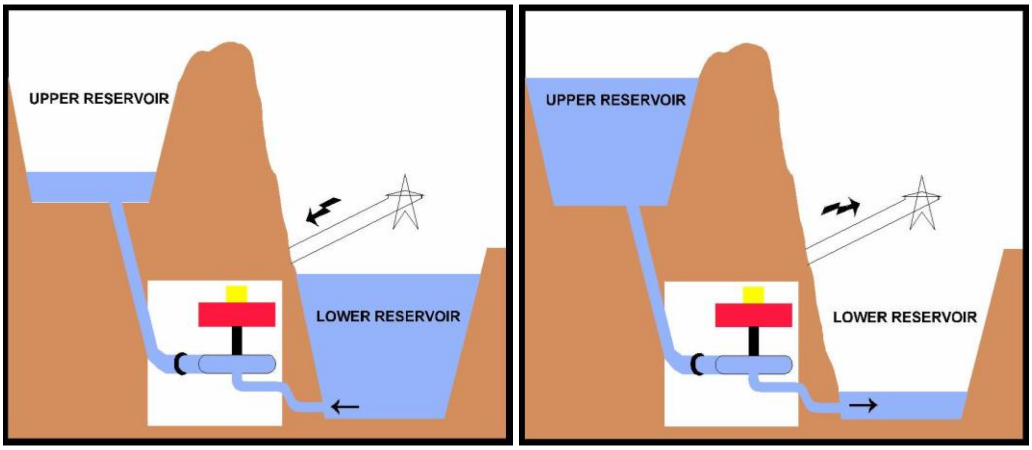
Abstract

With the large variation in electric daily load curves between day and night, the improvement in the shape of the load curve has appreciable benefits. Hydroelectric pumping stations can offer such a benefit so that water is pumped up from the downstream lake to the upper lake at low values of load, usually after midnight, and water is let to flow downward generating electricity at peak load period. Usual efficiency for such system is around 80%.

It is proposed in this paper to build a pumping station at King Talal Dam area. The topography of the surrounding area offers an ideal situation. The proposed design may have a reasonable payback period because of the big different of cost of electric energy generation between peak period and off peak period. Hence it can offer a good improvement in daily load curve.

1. Introduction

A pumped storage consists of lower and upper reservoirs with a power station/pumping plant between the two. During off-peak periods, when customer demand for electricity has decreased, the reversible pump/turbines use electricity from the national grid to pump water from the lower to the upper reservoir as shown in figure 1a below. During periods of emergency or peak demand, this water is allowed to run back into the lower reservoir through the turbines to generate electricity as shown in figure 1b below. In this way, the potential energy of water stored in the upper reservoir is released and converted into electricity when needed.



(a) (b)

Figure 1

The first use of pumped storage was in the 1890s in Italy and Switzerland. The 1890s were sometimes referred to as the " Mauve Decade" because William Henry Perkin 's aniline dye allowed the widespread use of that in Switzerland. In the 1930s reversible hydroelectric turbines became available. The 1930s were described as an abrupt shift to more radical and conservative lifestyles as countries were struggling to find a solution to the Great Depression. These turbines could operate as both turbine-generators and in reverse as electric motor driven pumps. The latest in large-scale engineering technology are variable speed machines for greater efficiency. These machines generate in synchronization with the network frequency, but operate asynchronously (independent of the network frequency) as motor-pumps (1)

There are more than 1000 pumping stations all over the world now, which are listed in reference (3). The five largest operational pumped-storage plants in the world are listed below(2):

Station	**Country**	**Capacity (MW)**
Bath County Pumped Storage Station	United States	3,003
Guangdong Pumped Storage Power Station	China	2,400
Huizhou Pumped Storage Power Station	China	2,400
Okutataragi Pumped Storage Power Station	Japan	1,932
Ludington Pumped Storage Power Plant	United States	1,872

Pumped storage is the largest-capacity form of grid energy storage available, and, as of March 2012, the Electric Power Research Institute (EPRI) reports that PSH accounts for more than 99% of bulk storage capacity worldwide, representing around 127,000 MW. PSH reported energy efficiency varies in practice between 70% and 80%, with some claiming up to 87% (2)

The technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors.(2)

Because of large energy losses in the transformation “electricity → water → electricity”, this process hardly saves energy but it can be profitable on financial grounds if: (i) the difference in the cost of electricity production between peak and off-peak periods is high and (ii) the losses implied by the double transformation are not too high.(4)

Hydroelectric Systems which are of power production of more than 100MW are known as Large-hydro; those of 15 - 100 MW usually feeding a grid are known as large. Third, Small-hydro is 1 - 15 MW - usually feeding to a grid also. Mini-hydro is above 100 kW, but below 1 MW. Micro-hydro is from 5kW up to 100 kW, usually provides power for a small community or rural industry in remote areas away from the grid. Pico-hydro is from a few hundred watts up to 5kW, remote areas away from the grid.

2. **Pros and Cons of Pumping Stations :**

- Pumped storage power stations are quick re-action to changes in electricity demand which play a major part in maintaining the stability of the national grid.
- They can also reduce harmonic distortions, and eliminate voltage sags and surges.
- They provide an alternative to peaking power by storing cheap base-load electricity and releasing it during peak hours.
- Pumped storage power stations can only provide energy for limited periods of time.
- They are more expensive to operate than conventional hydroelectric power stations because of their pumping costs.
- The deployment of PHES requires suitable terrains with significant elevation difference between the two reservoirs and significant amount of water resource.
- The construction of a PHES station typically takes many years, sometimes over a decade.
- Environmental impacts on animal sea when the lower reservoir is the sea itself.

3. **Main Components of the System**:

- Reservoir that needs to save water that acts much like a battery, storing water to be released as needed to generate power.
- Intake to prevent fish and wildlife from passing through any proposed energy generation equipment.
- Penstock is a pipe carries the water from the reservoir to the turbine.
- Turbine that converts the kinetic energy of fluids to mechanical energy that drives generator.
- Power House area will need to be established to contain turbines, pumps, machines and some other devices.

3.1 Operating Modes:

Under a proposed hydropower installation, either pumping or generation modes could occur at any particular time but not simultaneously. The system normally consists of two water reservoirs or lakes at different heights. These are connected by large diameter pipes or tunnels. Reversible pump / turbine machines are located in a power house connected to the pipes. These are first used to pump water from the lower to the upper reservoir, where it is stored as hydro energy. The pumps are powered by large electric motors, which can also act as generators in the reverse direction. When water is released from the upper reservoir, it flows back down through the reversible machines, which now act as turbines. The turbines are connected to reversible motor / generators, which were initially used as motors to drive the pumps, but now act as generators powered by the turbines and reconvert the hydro energy into electricity.

3.2 How to Measure Potential Power and Energy

- As an example, 1000 kilograms of water (1 cubic meter) at the top of a 100 meter tower has a potential energy of about 0.272 kW·h(2)
- Head is height between upper reservoir and lower reservoir.
- Flow is how much water moves through the system—the more water that moves through a system, the higher the flow.

4. Hydro Power Calculations :

Before a hydroelectric power site is developed, engineers compute the power that can be produced when the facility is complete. The actual output of energy at a dam is determined by the volume of water released (discharge), the vertical distance the water falls (head). So, a given amount of water falling a given distance will produce a certain amount of energy. The head and the discharge at the power site and the desired rotational speed of the generator determine the type of turbine to be used.

The theoretical power to be generated by a hydro-electric plant in horsepower or kilowatts can be computed as follows:

Power in turbine mode:

$$P = g\,\rho\,Q\,H\,\eta \tag{1}$$

Power in pump mode:

$$P = g\,\rho\,Q\,H\,/\eta \tag{2}$$

Where P = power in kilowatts (kW), g = gravitational acceleration (9.81 m/s^2), η = turbo-generator or pump-motor efficiency ($0< \eta < 1$), Q = quantity of water flowing (m^3/sec), H = effective head (m), ρ = fluid density in kilograms per cubic meter [kg/m3] = 1000 [kg/m3] for water. We can calculate turbo-generator or pump-motor efficiency from equations below:

$$\eta = \eta_{pump} \times \eta_{motor} \quad (3a)$$

or

$$\eta = \eta_{turbine} \times \eta_{generator} \quad (3b)$$

The flow rate is dictated by the expected volumetric area of the limiting reservoir divided by the desired storage time to yield the available flow. The effective head equal difference between gross head and head loss. Formula of flow rate as below:

$$Q = A \times \upsilon \quad (4)$$

Where, A= area of penstock, υ= velocity of water. And evaluate to variable from formula below:

$$A = \frac{\pi D^2}{4} \quad (5)$$

$$\upsilon = \sqrt{2gH} \quad (6)$$

5. Proposed System:

5.1 Location of Station:

The proposed location of our project is King Talal dam. The King Talal Dam is a large dam in the hills of northern Jordan across the Zarqa River shown in Figure 2.

Figure 2 King Talal dam showing the lower lake and the location of the upper lake

The King Talal dam was started in 1971, with the original construction being completed in 1977. In 1984, to meet the country's increased water demands, work to raise the dam further was begun, a project that was completed in 1988 at a cost of $90 million. We choose this location because that:

- The King Talal Dam is a big contribution to renewable energy in Jordan.
- The Gross Storage Capacity of the Dam is 86,000,000 m^3, the Live Storage Capacity is 78,000,000 m^3, and the Dead Storage is 8,000,000 m^3.
- It has a good head for upper reservoir.
- The King Talal Dam is near the center load of Jordan at Amman area.

The other comparable location can be at Aqaba, utilizing sea water as the lower lake and an upper lake at the mountains near the sea. A similar system using pumped sea water to store the energy is a 30 MW Yanbaru project in Okinawa was the first demonstration of seawater pumped storage. A 300 MW seawater-based project has recently been proposed on Lanai, Hawaii, and several seawater-based projects have recently been proposed in Ireland(2).

5.2 Jordan Electric System :

Table 1 shows the peak load of Jordan and the energy consumption (5)

Table 1 National Electricity Production Company (NEPCO) Figures

	2000	2005	2010	2011
Peak Load, MW	1160	1645	2545	2660
Purchased Energy, GWh	6535	9555	14562	15477
Imported Energy, GWh	45	982	670	1738
Sold Energy, GWh	6311	9219	14259	15132
Exported Energy, GWh	--	0.3	58	86
Transmission lines length, km-circuit	2945	3400	4035	4121
Main Substation Capacity, MVA	3589	5989	9657	10023
Transmission losses, %	3.28	3.52	2.08	2.23

Electricity energy sold in Jordan amounted to (15132) GWh in the year 2011 against (14259) GWh in 2009, with an annual increase of (6.12%). The peak load amounted to (2660) MW in 2011**.**

A sample for summer load is shown for 22-6-2011 in Figure 3. It shows that the peak load occurs at 12:00 pm which reached to (2232) MW, but minimum load occurs at 5:00 am which reached to (1441) MW.

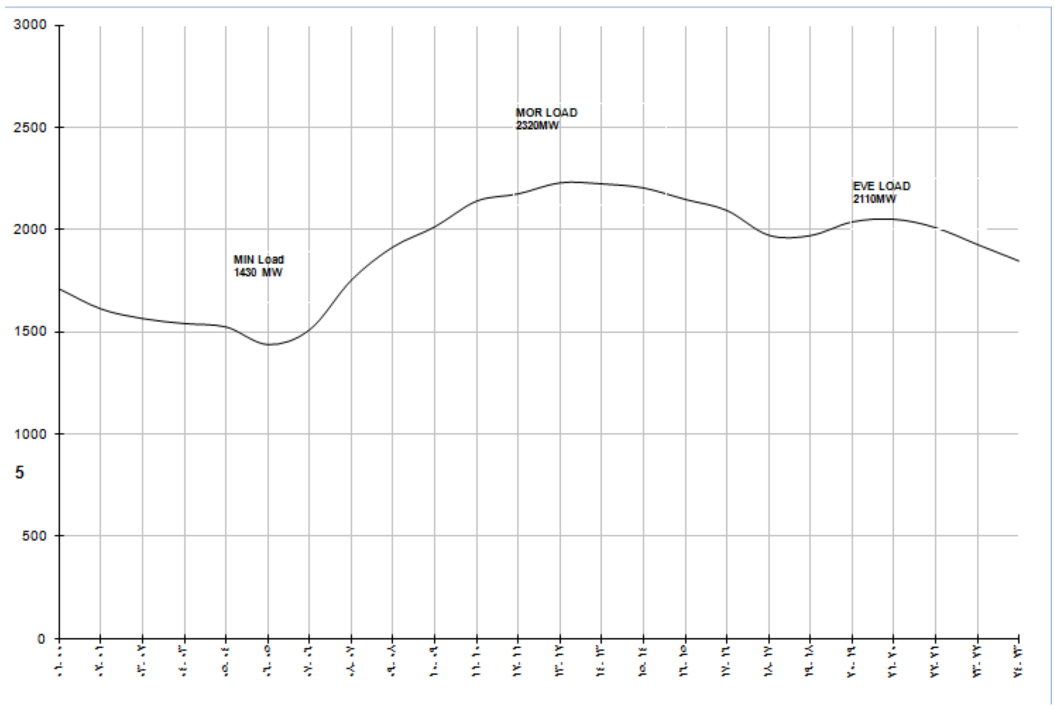


Figure 3 A daily load for 22-6-2011

It is a fact that the cost of energy in base load is less than peak load; because some plants are relatively inefficient and burn expensive fuel. Table 2 shows the cost of energy at different power stations in Jordan as was in February 2012. But the cost of electrical energy on consumers is relatively low compared to cost of generation.

Table 2 Generating Stations in Jordan

STATION	Type of fuel	Average cost @full load (JD/Mwh)	Capacity MW
ATPS	GAS	42.5	130
AES CC	GAS	30.9	430
AES SC	GAS	47.1	145
SAMRA CC 2	GAS	32.3	315
SAMRA CC 1	GAS	31.5	315
SAMRA 3+4 SC	GAS	50.7	100
SAMRA 5+6 SC	GAS	46.1	142
QATRANAH CC	GAS	30.6	373
QATRANAH SC	GAS	47.5	127
REHAB SC	GAS	49.3	99
REHAB CC	GAS	33.6	290
REHAB 10 , 11	GAS	55.5	30
SAMRA CC	DSL	117.4	315
REHAB CC	DSL	107.4	290
SAMRA SC (5)	DSL	172.1	142
SAMRA 3+4 SC	DSL	193.5	100
AES CC	DSL	105.3	430
ATPS	Fuel	132.6	600
HTPS (66)	Fuel	160.2	264
HTPS(33)	Fuel	173	99
Resha	DSL	204	126

5.3 Proposed System Design Requirements

Optimal hydraulic design is very important in the selection of pumping station design schemes. Through optimal hydraulic design of pumping system it is possible to generate better flow conditions for pump, to reduce hydraulic losses both in suction box and discharge passage and improve pumping system efficiency.

The optimal object of suction box is to conduct water smoothly from intake to the entrance of pump, to provide better flow conditions for pump, to reduce hydraulic loss as much as possible and satisfy requirements in civil and hydraulic structural design as well as equipment arrangement, and so on. Specifically speaking, it is as follows.

(a) Reasonable dominating dimensions, favorable shape and size, smoother interior surfaces without flow separation and vortex or other bad flow patterns inside the suction box.

(b) The changes of cross-sectional area along the direction of flowing water should be well distributed, and the velocity and pressure distribution in the outlet section of the suction box should be symmetrical as much as it could be, generating better flow conditions for pump.

(c) The appropriate approaching velocity of water in the inlet of the suction box is in the order of 0.8～1.0m/s.

(d) Cut down the hydraulic loss of suction box as much as possible.

The optimal design of discharge passage should satisfy the following requirements.

(a) The change of cross section in shape and size should be done smoothly and gradually. The value of diffusive angle in the longitudinal direction should be appropriately taken, usually within 8°to 12°, to avoid flow separation and vortex or other bad flow patterns inside the discharge passage.

(b) The velocity of flow water in the outlet section of the discharge passage should not exceed 1.5m/s, to facilitate reclaiming dynamic energy of flowing water, and greater velocity is inadvisable.

(c) Cut down the hydraulic loss of discharge passage as much as possible.(6)

5.4 King Talal Proposed Pumping Station:

The project site is located in King Talal dam to the north of Jordan across the Zarqa River. This site has a potential hydraulic head about 190 meters between the top and bottom reservoir. The estimation of the capacity of the proposed pumping station shall depend upon the available water for pumping and the topography of the site.

The Gross Storage Capacity of the King Talal Dam is 86,000,000 m^3, the Live Storage Capacity is 78,000,000 m^3, and the Dead Storage is 8,000,000 m^3. So utilizing a quantity of water of 3,000,000 m^3 would be reasonable. An upper reservoir of 17m height would have a surface area of about 176,470 m^2. Such a lake may have the dimensions of approximately 420*420*17m. Such area is available on the hill near the dam. The reservoir could have an energy storage capacity of 1325.1 MWh deployable in 6.33 hours at 209.6 MW in generating mode. But to pump this capacity we need 1795.125 MWh by the same time for storage at 299.188 MW. In two mode flow rate - almost constant - are estimated about 131.8 m^3 /s. Dependent on above, the calculated overall efficiency of the system is about 73.82%.

PHES has pumped hydroelectric energy storage infrastructure in the ground today that may be utilized to facilitate the integration of renewable generation onto national electric grid. The proposed capacity of generation of about 209.6 MW, which may operate instead of some plants which operate on fuel and diesel may improve load curve as shown figure 4 and 5. The plants may generate power at peak load which cost national electric grid more than 80 JD/MW. But at night, the pumping power to the upper reservoir would need 299.188 MW for 6 hours at a rate of approximately 45 JD/MW.

Figure 4 show daily load curve for 22-6-2011 which shows how the daily load curve would approximately look like after the installation of PHES. The green color is quantity of power used for pumping water up and the red color approximately shows the generated energy from the system at around peak load. Another example is Figure 5 which shows the daily load curve for 10-1-2011. Dependent on these informations, we can estimate payback period about it. The net annual energy difference of this station is estimated to be around 6,537,276 JD.

This estimate is based upon estimated cost of fuel. The new regulation in Jordan for purchase of energy from renewable sources does not include prices for hydroelectric sources. Based on consultation with civil engineers and with comparison with similar projects elsewhere the estimated cost of the project is about 100 million JD. Accounting for assumed future increases in the cost of energy, the simple payback period for this project is 15 years. The estimated lifetime for such hydroelectric project is 35 years. It mean that it is much more than payback period. It is worth mentioning that with the capacity of station of 209.6 MW as mention above this mean that the cost for KW is 477 JD/KW.

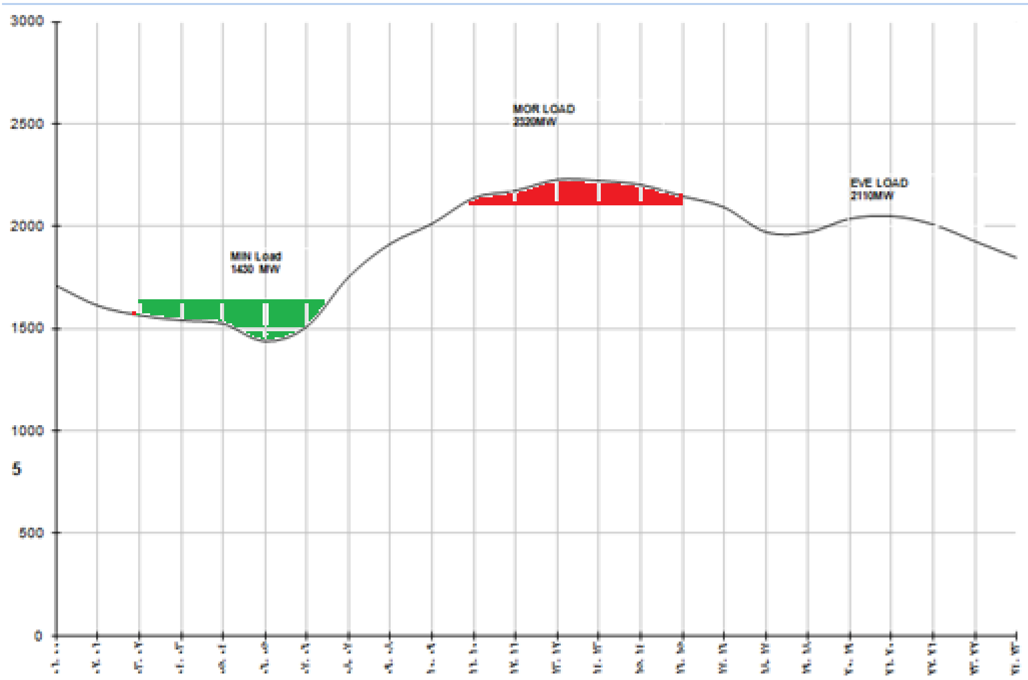


Figure 4 Daily load curve for 22-6-2011

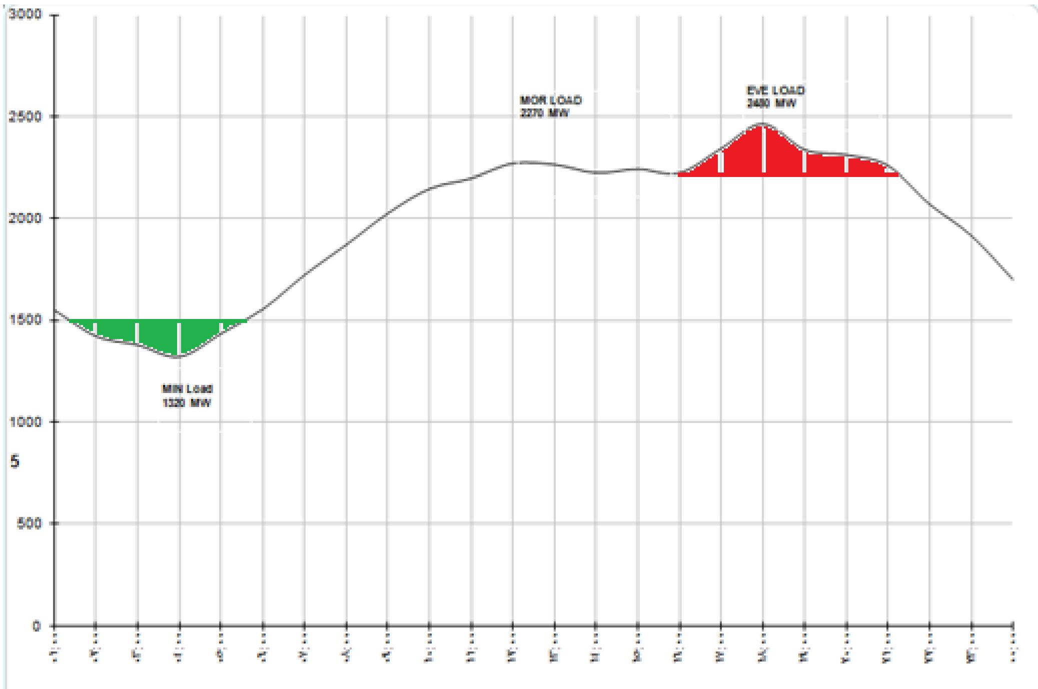


Figure 5 show daily load curve for 10-1-2011Figure 5

The usual overall efficiency of the PHES systems could be between (70% -84%). The proposed system's efficiency is 73.82% which may be raised by further improvement in the design. The most effective parameter on overall efficiency is the head. This needs changing architecture of the system by making the head of turbine mode and the head of pump mode to be different. The first step to change architecture is to increase the volume of upper reservoir because some of the water is not used in operation. The second thing is that we may put the head of the pump pipe on a height less than head of turbine pipe; figure 6 shown below clears the architecture of this design. Such a design may increase the volume of reservoir to 3,500,000 m^3 and the height of pump pipe to become 187 m but the height of turbine pipe 190 m with overall efficiency may increase to 75% when we neglect water force over pipe in pump mode.

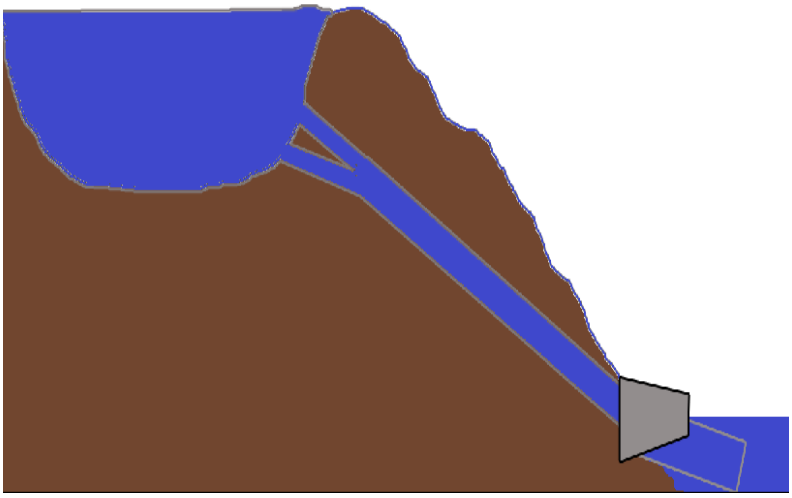


Figure 6

The cost of power depends on cost of construction and cost of alternative electricity cost in Jordan. These factors determine the cost of sold power at 80 JD/MW to provide adequate payback period for the system and help the grid to decrease cost of power generation. In order to define the critical cost of power generation which make the save of day equals zero, this cost is 61 JD/MW. This means no benefit from the system. Also if the cost of generation below the selected value then the payback period isn't adequate. For example if cost of generation is 65 JD/MW then save of a day is 5,350 JD and annual save is 1,947,718 JD so that the payback period is 50 years.

World experience is that hydro projects cost about US$2,000/kW to US$4,000/kW. The Electricity Storage Association gives a range of costs for Pumped-Hydro of US$500/kW to US$1500/kW. This project is estimated at 672$/kW.(2)

PHES is helping to meet the needs of Jordan, and one of the most pressing needs is the growing demand for electric power. PHES is important from an operational standpoint as it needs no "ramp-up" time, as many combustion technologies do. PHES can increase or decrease the amount of power it is supplying to the system almost instantly to meet shifting demand. With this important load-following capability, peaking capacity and voltage stability attributes, PHES plays a significant part in ensuring reliable electricity service and in meeting customer needs in a market driven industry. In addition, PHES facilities are the only significant way currently available to store electricity.

PHES's ability to provide peaking power, load following, and frequency control helps to protect against system failures that could lead to the damage of equipment and even brown or blackouts. Hydropower, besides being emissions-free and renewable has the above operating benefits that provide enhanced value to the electric system in the form of efficiency, security, and most important, reliability.

Based on the elastic model of hydraulic system with reasonable order, and the linear models of turbine generator and governor, the analytical model for effect analysis of load characteristic on operation stability is built according to the state equations method, and further numerical verification analysis is conducted for two given cases. The results indicate that, regulation performance of unit with water pumping system (dynamic load) is superior to that of resistance (static load). (7)

From financing point of view, this scenario can be useful if there is shortage of natural gas in Jordan so that we use diesel or fuel plants which cost in generation much more than PHES, but if natural gas is available cheaply, the PHES will not be so economical.

5.5 Proposed System Main Characteristics

The following are the proposed characteristics of the system design:

- Reservoir
  The upper reservoir depth - 17 m & store 3,000,000 m^3.
  The lower reservoir store - 86,000,000 m^3.
  Head - 190m.
- Penstock
  The diameter - 165 cm.
  The length of pipe - 190 m.
  Flow - 131 m^3/s.
- Turbine & Pump
  Francis turbines - operate as turbine & pump.
  Efficiency - 90%.
- Machine
  Synchronous Machine - generator/motor.
  Frequency & Speed - 50 Hz & 1500 rpm.
  Rated Power - 300 MW.
- Capacity & efficiency
  Generating Mode - 209.6 MW for six hours.
  Pump Mode - 299.188 MW for six hours.
  Overall Efficiency - 73.82%.
- Cost Estimate
  Construction Cost - 100,000,000 JD.

Revenue Cost

- Saved of day - 25227.375 JD.

NOTE : (Pturbine * Cost of sold * Time storage) – (Ppump * Cost of night energy * Time storage).

- Annual kWh purchase and sales differential - 6559117.5 JD.

NOTE : Saved of day * 5 day/week * 52 weeks/year .

- Operation and Maintenance Cost - 21,841 JD.

Total save of year_- 6537276 JD.

Avoided Peak Generation Cost

HTPS (66) fuel - 80.2 JD/MWh.

Risha diesel - 124 JD/MWh.

SAMRA (5) SC diesel - 92.1 JD/MWh.

NOTE : (diesel or fuel plant generation cost) – (Pumped hydro generation cost).

6. Conclusions:

Hydroelectric pumping station is a way for improving daily load curve and to improve the overall cost of generation of electricity in Jordan. It can improve stability and overall performance of the power system. It is shown in this paper that the proposed project at King Talal dam is a feasible system which needs further studies from environmental and ecological points of view. Similar study for a pumping station at Aqaba is also suggested to pump sea water.

7. References

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