Challenges of integrating a small hydropower plant at existing Mujib dam

N. Al-Shnynat

Jordan Valley Authority, Ministry of Water and Irrigation,
Amman 11183, Jordan

nidal.shnynat@gmail.com

ABSTRACT. *Despite Jordan's crucial situation of energy sector where almost all of Jordan's demand is covered by importing combustible fuels, which is affected by international cost fluctuation in addition to political situation in the nearby region. Merely recently the country has started harnessing its own potential resources and looking into more sustainable solutions mainly in Solar and Wind sectors. As well as, only two sites of Hydropower plants, King Talal Dam & Cooling System of King Hussein Thermal Power Station, are exploited to produce electricity with an estimated design power of 5MW, for each. In this manuscript, the situation of energy in Jordan will be briefly introduced along with a short overview of Hydropower in the country, and the potential of integrating a small hydropower plant at Mujib dam by adopting worst case scenarios of reservoir water levels and discharge flow according to the regulations by Jordan Valley Authority (JVA). Also, the use of existing dam infrastructure will be taken into account in order to minimize the capital cost. Moreover, environmental, social, and financial constraints will be focused upon throughout this study.*

RÉSUMÉ. *Malgré la situation cruciale du secteur de l'énergie en Jordanie, la quasi-totalité de sa demande est couverte par l'importation de combustibles, qui subit les fluctuations des coûts internationaux en plus de la situation politique dans la région voisine. Récemment, ce pays a commencé à exploiter ses propres ressources potentielles et à rechercher des solutions plus durables, principalement dans les secteurs de l'énergie solaire et de l'énergie éolienne. De plus, seuls deux sites de centrales hydroélectriques, King Talal Dam & Cooling System of King Hussein Thermal Power Station sont exploités pour produire de l'électricité avec une puissance de conception estimée de 5 MW chacun. Dans ce manuscrit, nous présenterons brièvement la situation de l'énergie en Jordanie, ainsi qu'un bref aperçu de l'hydroélectricité dans le pays et du potentiel d'intégration d'une petite centrale hydroélectrique au barrage de Mujib en adoptant les pires scénarios de niveaux d'eau de réservoir et de flux de décharge conformément aux règlements de la Jordan Valley Authority (JVA). De plus, l'utilisation des infrastructures de barrage existantes sera prise en compte afin de minimiser le coût en capital. De plus, les contraintes environnementales, sociales et financières seront au cœur de cette étude.*

KEYWORDS: *hydro-power, cross flow turbine, renewable energy.*

MOTS-CLÉS: *hydroélectricité, turbine à flux croisés, énergie renouvelable.*

DOI:10.3166/EJEE.20.181-191

1. Introduction

Looking at Jordan's situation of energy; its high demand and consumption, yet low production, it can easily be labeled as deprived of energy. For example, in 2016, Jordan's production out of crude oil was merely 0.5 ktoe. However, its crude oil demand was thousands of times higher as it consumed 5327 ktoe, in one year alone. Also, the same case for natural gas, Jordan's production was equivalent to 101.1 ktoe, yet its consumption of natural gas was 3389 ktoe (Ministry of Energy and Mineral Resources of Jordan (MEMR), 2016). These numbers alone show how heavily Jordan needs to seek other solutions, such as importing crude oil and natural gas, to make up for its shortage in production and cover its demand. In 2016, in the transport sector alone Jordan's demand was equivalent to 3184 ktoe. In Industry and for domestic needs, the demands were 1064 ktoe and 1342 ktoe, respectively. In addition, for other sectors like commercial, agriculture, and street lighting, the demand was 826 ktoe (MEMR, 2016).

However, due to the political conflicts in the nearby regions among the years, and the unstable situations in export-countries, Jordan started looking closer into the bigger picture of finding constant and reliable solutions to cover its energy burdens. Therefore, it started taking renewable energy resources into consideration and Jordan's consecutive governments made several attempts to utilize Jordan's natural resources and engage it in renewable energy resolutions in order to cover its continuously growing demand on electricity. And so on, Jordan updated its master strategy of energy sector for the period of 2015–2025, in order to make full use of its renewable energy resources for electricity generation. Thus, "The total capacity of renewable energy projects, both solar and wind, for the end of 2018 will be 1132 MW where it will form 20% of the combined generating capacity and contributes about 9% of the electricity produced" – MEMR Strategy 2015 – 2025 (MEMR, 2016).

Nevertheless, an alternative and efficient solution would be none other than Hydropower, as hydropower plants easily achieve efficiencies of 75% to 95%, as well as, it covers 19% of the worldwide electricity demand (World Energy Council, 2016; Penche, 1998). An even more nifty solution would be the utilization and development of small hydropower (SHP) plants on existing hydro-structures, specifically existing dams, as it promotes new attractive and feasible solutions for various reasons. Mostly, there are little to no further environmental or social adverse effects on the nearby of the proposed hydro-structure to be retrofitted with hydropower turbines, because they are already demarcated. Also, the use of existing water infrastructure will significantly reduce the overall cost of the plant. In addition, introducing a hydropower plant on existing hydro-structure will improve the surrounding economic and social sectors.

2. Small hydropower

The design philosophy of the system and parts of a small hydropower plant is similar to that of large-scale hydropower plants, except that the systems are mostly simpler. However, the definition of Small Scale Hydropower differs from one country to another; nevertheless, the most common approach for defining Small Scale Hydropower is to give it an upper generation capacity limit of 10MW (ESHA, 2004).

The newly and continuously developed technology of small hydropower promotes various benefits and has slight effect on the environment, because it utilizes small or no reservoir, a portion of watercourse used for power generation, and has less influence on natural flow (WSHPDR, 2016).

Small Hydropower plants are a clean energy source, as it does not produce waste in rivers, nor pollute the air with greenhouse gas emissions. In addition, small hydropower plants can be fish-friendly if well equipped with proper fish ladders and fish friendly blades, as well as, it ensures minimum flow downstream in order to reserve flow that guarantees fish life (JVA, 2017).

Small hydropower is an excellent renewable energy solution as it adheres to the classification of being renewable by using water as fuel for the plant, which is not consumed by the electricity generation process. It also provides economical solutions as it has the lowest electricity generation prices of all off-grid technologies). It mobilizes financial resources and contributes to the economic development of small disperse populations, ensuring autonomous and reliable energy for the long term. In addition, it creates local jobs for the monitoring of the running phase of the plant (WSHPDR, 2016). Small Hydropower can also be used for purposes other than electricity generation such as water supply as drinking water or for irrigation, and it promotes recreational activities like fishing, swimming, and boating.

Small hydropower schemes promote high-energy payback ratio, for each power generation system. The “energy payback” is the ration of energy produced during its normal life span, divided by the energy required to build, maintain, and fuel the generation equipment. If a system has a low payback ratio, it means that much energy is required to maintain it and this energy is likely to produce major environmental impacts.

3. Jordan potential in small hydro power scale

The geography and topography of Jordan supports the potential of small hydropower development. However, even though Jordan has 14 existing dams, only one dam is being used for electricity generation whereas the others are used mainly for drinking water supply and irrigation (JVA, 2017). As reminded by Jaber (2012), if the existing dams were to be retrofitted with small hydropower plants it would generate a potential of 33.2MW. Whereas, the potential of generating hydropower from proposed dams in Jordan will account for 24.92MW. In addition, another important proposed scheme that would change the total situation of the region by generating a capacity of 800MW would be the Red Sea-Dead Sea water conveyance project.

Even though, Jordan’s potential of small hydropower is 58.15MW, only two sites are exploited to hydropower. King Talal Dam on Zarqa River with design capacity of 5MW. Moreover, Aqaba thermal power station, utilizing the returning cooling seawater to produce 5MW. Below Figure 1 shows installed and potential Hydropower in Jordan (UNIDO and ICSHP, 2013).

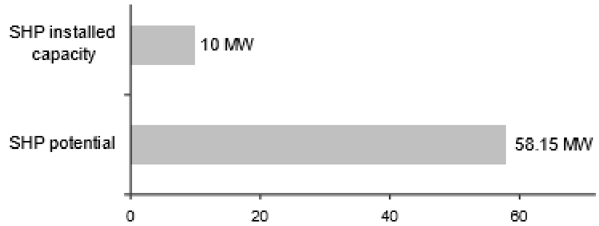

Figure 1. Installed and potential of Jordan’s small hydropower

4. Mujib dam

As reminded by JVA (2017), Mujib dam is one of Jordan's major dams located 80 km south of Amman city. The dam is constructed from RCC (Roller Compacted Concrete) in the center with embankment abutments. The dam height is 62 m and its catchment area accounts for 4380 km^2. The reservoir is designed to store 31.2 Million cubic metres of water. The dam utilizes three intakes for water entry on different levels, 165, 175, 185 above sea level (ASL). These intakes are connected to a penstock and its accessories to draw off water from the reservoir. And it was launched in 2003 for the purposes of:

-To contribute to providing irrigation water for the southern Ghor irrigation project and to improve water quality in Mujib valley.

-To contribute to providing water to developments on the east shore of the Dead Sea.

-To contribute to providing water needed for future expansion of the Arab Potash Company and Dead Sea Chemical Complex.

-To supply Amman city with drinkable water.

5. Methodology

Retrofitting of existing dams with small hydropower enables for generating electricity in rural areas around dams, which eliminates unnecessary transmission, distribution losses, and cost, as well as, reduces emissions resulting from fossil fuels. However, in order to retrofit a dam with a small hydropower plant, one needs to conduct necessary studies for design of SHP, summarized below:

-Topography and geomorphology

-Evaluation of the water resource and its generating potential.

-Site selection and basic layout.

-Electromechanical equipment and their control.

-Environmental impact assessment and mitigation measures.

-Economic evaluation of the project and financing potential.

-Institutional framework and administrative procedures to attain the authorizations.

In this paper, an introductory investigation of the possibility of retrofitting Mujib dam with small hydropower to generate electricity is studied. The daily water level and its equivalent water storage in the reservoir of the dam are measured automatically, and collected by the dam unit at JVA on a daily basis since the launch of Mujib dam (JVA, 2017).

This data is used and manipulated to calculate the discharge, gross head, net head that is used for power and energy estimations. The data examined in this paper is that of summer months (May, June, July, August, and September) during 10 years span (2007 to 2016). As the JVA unit did not use a flowmeter to measure the discharge, Along with the fact that there is no rain in the dam's catchment area in summer season that could affect the elevation difference; one can simply take the daily storage difference, daily evaporation, and daily seepage to calculate the discharge from the dam. Another key factor variable needed for the calculations is the hydraulic gross head, which mainly depends on the level of water in the reservoir. This level varies according to the quantity of water that is collected by the dam. This water depends on seasonal flooding that is coming from the catchment area of the dam, which extends on huge areas in the surrounding eastern desert bringing with it enormous amount of sediments, specially fine sediments.

Sediments inflicts a challenge on the dam as the fine sediments will settle along the body of the dam, and with time it will accumulate to reach higher levels that might block the intake of the dam. In the case of Mujib dam, this situation is true and the first intake at level 165 ASL is almost blocked. In addition, the demand on drinkable water for Amman or irrigation water for southern Ghor or industrial needs of Arab POTASH company could actually affect the head indirectly, in others words, if the demand increases, the regulations of JVA will be altered to accommodate these demands, therefore, the more reservoir water consumption will result in a decreased head. Hence, according to data and the above-explained situation of the dam, along with the consideration of current existing penstock; the reasonable intake level is 175 ASL, which is the level of the second intake of Mujib dam (JVA, 2017). However, all intakes will be taken into consideration. In addition, the location of the proposed turbine will affect the value of gross head, however, as a worst-case scenario calculations, the installation of turbine at the end of the penstock (140 ASL) is implemented in this study.

6. Results and discussions

From the collected data, two cases is highlighted, the average gross head of 46 m and the average discharge of 0.41 m^3/s as case 1. In addition, the maximum gross head of 54 m and the maximum discharge of 1.06 m^3/s as case 2. Below shown in Figure 2 is the variable discharge throughout the years 2007 to 2016, summer months.

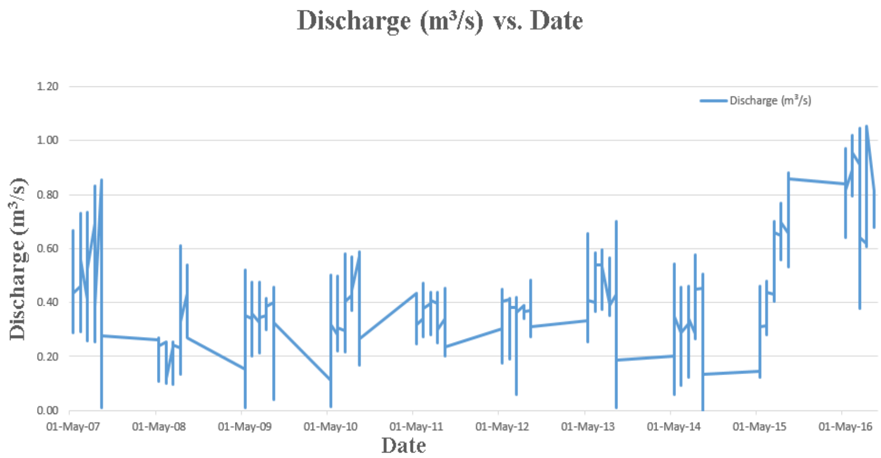

Figure 2. Discharge amongst the years 2007–2016

6.1. Net head calculation

In order to calculate the net head, certain losses need to be calculated. In the case of penstock losses, it is considered a closed conduit therefore; it has friction, bend, and valves losses. In a hydro-plant, the most important losses that affect the net head come from friction. A well-known formula to estimate friction losses is that of Manning:

$$H_f = \frac{10.29n^2Q^2}{D^{5.333}} \tag{1}$$

Where D is the diameter of penstock, L is the length of penstock, and n is the Manning coefficient, which is to be 0.012 for Welded steel. Additionally, the other losses of screen (H_{scr}), entrance (H_e), bend (H_b), and valves (H_v). The summation of these losses (H_{sum}) can be found using the equation below:

$$H_{sum} = (k_{scr}\left(\frac{t}{b}\right)^{1.33}\sin\emptyset + k_e + k_b + k_v)(\frac{v^2}{2g}) \tag{2}$$

Where, k_{scr}, k_e, k_b and k_v are the coefficients of losses for screen, entrance, bend, and valves, respectively. (t) and (b) are the thickness of bar and width between bars, ($\emptyset$) is the angle of rack inclination form horizontal, and (v) is the flow velocity. The net head can be calculated by the following formula:

$$H_{net} = \text{Z} - (H_f + H_{sum}) \tag{3}$$

The above formulas, reminded by Aslan *et al*. (2007) and Layman (1998), are applied on the data shown in Figure (3); it is found that the overall losses accounted for a maximum of 9.72m and an average of 1.82m. Therefore, the net head ranged between 32m to 54m, with average of 44.27m.

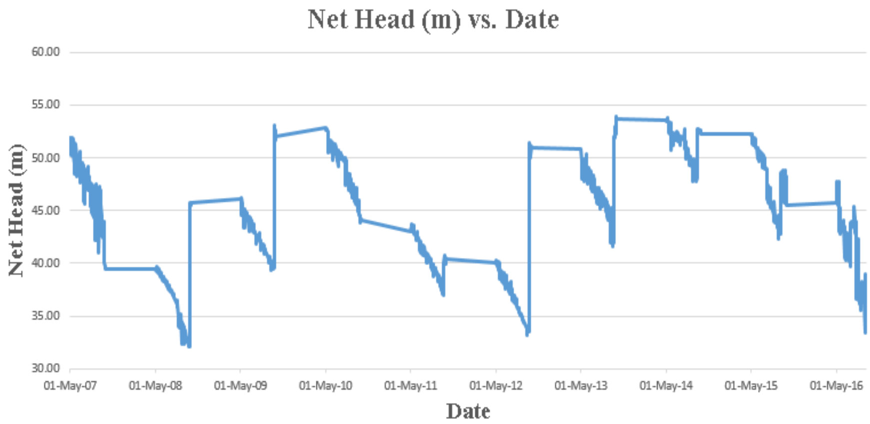

Figure 3. Net head amongst the years 2007–2016

6.2. Determination of turbine types

According to the chart below (Layman, 1998) along with the dam-collected data together with the net head values, crossflow and semi-kaplan turbines meet the requirements. However, since the determining data sits at and exceeds the border of Kaplan turbine in the chart below, and the studied dam has fluctuating flow rate depending on the downstream demands together with the characteristics of adjustable guide vanes in Kaplan turbines, it has poor part-flowrate efficiency. Therefore, crossflow turbines are the most suitable turbines to be retrofitted onto Mujib dam. Crossflow turbines displayed in (Figure 5) (Okot, 2013) acquire their name from the manner the water flows through, or more fittingly 'across' the rotor, hence across flow or crossflow. The water flows over and under the inlet guide-vane, which guides flow to guarantee that the water hits the rotor at the accurate angle for maximum efficiency. The water then flows over the upper rotor blades, creating a torque on the rotor, then through the center of the rotor and back across the low rotor blades producing more torque on the rotor. One of the benefits of crossflow turbines are that they are self-cleaning by washing off leaves and debris that get trapped on the upper blades; by the departing water on the lower blades. Also, the centrifugal force tends to throw stuck debris outwards, further increasing the self-cleaning capabilities. Another advantage is the inlet adaptor of the crossflow turbine, the round to square adaptor, as it allows the turbine to fit directly on the supply pipe, penstock in the case of Mujib dam; collecting all discharge water flow. In addition, since crossflow turbines are categorized under impulse turbines, the rotor spins air and is not fully flooded like in reaction (e.g. Kaplan) turbines, thus making use of both, full or part flows by utilizing net and suction heads, respectively.

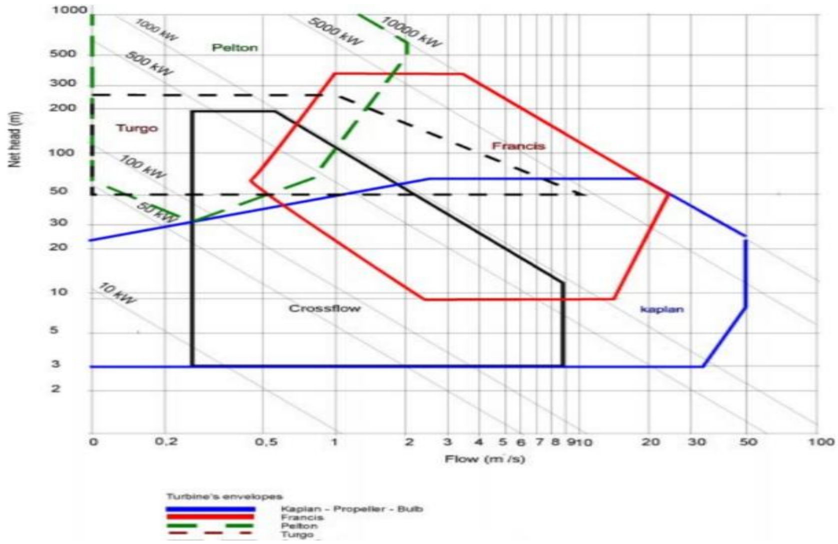

Figure 1. Turbines range of operation

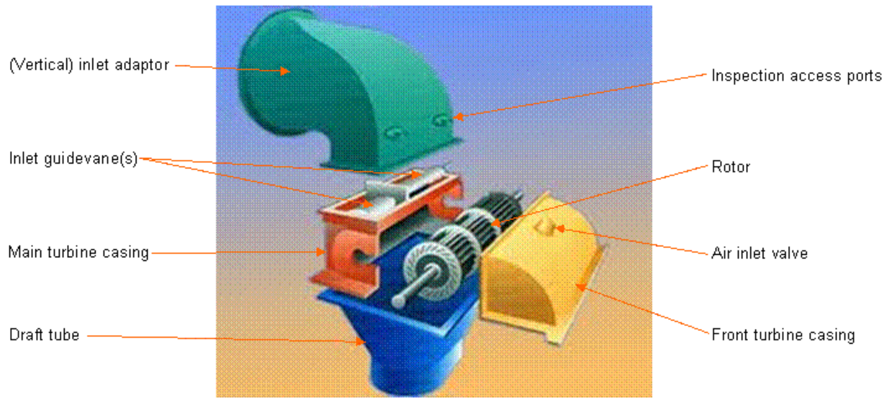

Figure 5. Crossflow turbine parts

6.3. Determination of power generation

The output power generation can be achieved through energy approximation given by the formula (Aslan, 2007):

$$P = \eta.\gamma.H.Q \tag{4}$$

Where P is output power (W), η is efficiency (%), γ is specific weight (N/m^3), H is net head (m), and Q: is flow rate (m^3/s). Assuming an efficiency to be that of typical hydropower plant's minimum efficiency value, which is around 75%, and Specific weight of water at 25℃=9777 N/m^3.

At Q=0.41 m^3/s, the power ranged between 96.458 kW to 162.31 kW with average of 133.1kW. At Q=1.06 m^3/s, the power ranged between 249.38 kW to 419.64 kW with average of 344.1 kW. When calculating for energy output, according to the operation and maintenance staff of Mujib dam, the dam is in operation for 300 days per year. Therefore, at Q=0.41 m^3/s, the estimated yearly generated energy ranged between 694.5 MWh to 1168.63 MWh with average of 958.23 MWh. At Q=1.06 m^3/s, the estimated yearly generated energy ranged between 1795.54 MWh to 3021.41 MWh with average of 2477.4 MWh. Keeping in mind that the above cases of discharge (Q=Average, Maximum) remain in the range of crossflow turbine operation.

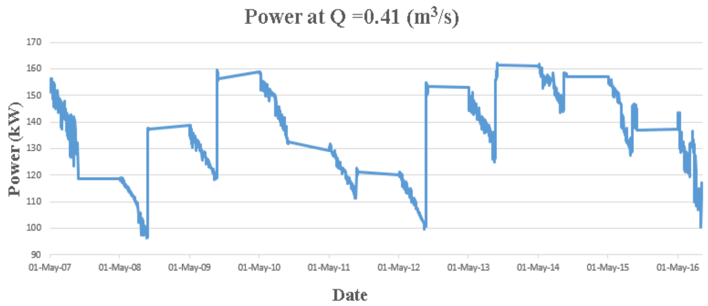

Figure 6. Power in kW at average discharge

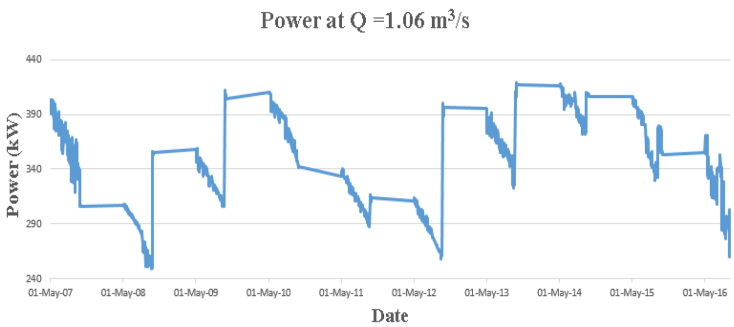

Figure 2. Power in kW at maximum discharge

7. Challenges and perspectives

Retrofitting of existing water infrastructure with hydropower to produce electrical energy can be a low-hanging fruit project, as there is no need for infrastructure construction along with its paper work for permissions and ownership of lands. In addition, the environmental and social constraints are mostly defined (Marence *et al*., 2016; Vuuren *et al*., 2011).

There is no effective base flow supplying the Mujib dam, and the reservoir depends solely on seasonal floods from the widespread catchment area. In addition, in the last years, Jordan suffered from several droughts and reduction in seasonal rainfall, which negatively affects the water quantity in the dam.

The sediments impose a huge challenge; as there is a continuous settlement of fine sediments in the reservoir, and the first intake is almost blocked. JVA has recently started studying several plans to counter measure this accumulation of sediments with the aid of international donors.

The demands of water downstream the Mujib dam changes unpredictably, which can be a challenge that greatly controls the output discharge and the energy generation.

High capital costs of small hydropower systems can dampen the attention for hydropower feasibility studies and implementation plans.

In contrast to developed countries, Jordan regulations prohibit the private sector to utilize the potential sites for hydropower generation, and the decision of harnessing potential hydropower lies solely within the hands of the government.

Jordan's consecutive governments out looked hydropower generation potential in Jordan is their strategies for future energy generation specifically the exploitation and potential of Small hydropower. Such studies may contribute to bring the governments' attention to the huge potential of small hydropower in Jordan.

8. Conclusions

Jordan highly depends on importing conventional fuels, crude oil and natural gas. It recently updated its master strategy to accommodate the utilization of renewable energy, focusing on solar and wind, out looking other potentials, such as hydropower.

Hydropower is a clean and admirable renewable energy solution, with low payback ratio. In addition, it contributes to the economic development and hydropower plants can be used for purposes other than power generation.

Retrofitting existing water infrastructure with hydropower can be a cheaper solution for power generation since almost most constraints are already defined. In addition, it will extend the life span of existing infrastructure, as it will attain extra attention concerning maintenance.

Mujib dam has a good potential to produce electrical power from being retrofitted with small hydropower even without altering its design or infrastructure; as in this case it will generate power that can be used to operate the dam and supply the nearby bedwins' tenants with power, without the need for power transmission.

Crossflow turbine best suits the situation at Mujib dam, of variable flow, with utmost efficiency.

References

Aslan Y., Arslan O., Yasar C. (2007). A sensitivity analysis for the design of small-scale hydropower plant: Kayabogazi case study. *Renewable Energy,* Vol. 33, No. 4, pp. 791-801. https://doi.org/10.1016/j.renene.2007.04.011

Gabriel C. D. (2015). Designing a small hydro power plant capable of producing 10 MW of electricity at webuye along river Nzoia. Final Year Project University of Nairobi. pp. 1-61.

Jaber J. O. (2012). Prospects and challenges of small hydropower development in Jordan. *Jordan Journal of Mechanical and Industrial Engineering,* Vol. 6, pp. 110-118.

Jordan Valley Authority (JVA). (2017). Mujib dam reports. Operations and Maintenance directorate.

Layman. (1998). Layman’s handbook on how to develop a small hydro site. European Commission. Belgium.

Marence M., Franca M. J., Tesgera S. (2016). Integration of hydropower plant within an existing weir - "a hidden treasure". *Sustainable Hydraulics in the Era of Global Change,* pp. 974-978.

Ministry of Energy and Mineral Resources of Jordan. (2016). Updated Master Strategy of Energy Sector in Jordan for the period (2007-2020). Amman. Jordan.

Ministry of Energy and Mineral Resources of Jordan. (2017). Annual Report–2016. Amman. Jordan.

Okot D. K. (2013). Review of small hydropower technology. *Renewable and Sustainable Energy Reviews,* Vol. 26, pp. 515-520. https://doi.org/10.1016/j.rser.2013.05.006

Penche C. (1998). Guide on How to Develop a Small Hydropower Plant. *Thematic Network on Small hydropower (TNSHP)*.

Sachdev H. S., Akella A. K., Kumar N. (2015). Analysis and evaluation of small hydropower plants: A bibliographical survey. *Renewable and Sustainable Energy Reviews*, Vol. 51, pp. 1013-1022. http://dx.doi.org/10.1016/j.rser.2015.06.065

United Nations Industrial Development Organization (UNIDO) and International Centre on Small Hydro Power (ICSHP). (2013). World small hydropower development report 2013-Jordan.

United Nations Industrial Development Organization (UNIDO). (2016). World Small Hydropower Development Report 2016.

Vuuren S. J. V., Blersch C. L., Dijk M. V. (2011). Modelling the feasibility of retrofitting hydropower to existing South African dams. *African Journals Online (AJOL),* Vol. 37. No. 5, pp. 679-692. http://dx.doi.org/10.4314/wsa.v37i5.5

World Energy Council. (2016). World Energy Resources, Hydropower Report-2016, World Energy Council.