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Seasonal-Water Dams: A Great Potential for Hydropower Generation in Saudi Arabia

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Abstract

For so many decades, hydropower generation has been one of the most attractive and effective methods of electricity generation around the world. However, when it comes to countries with low or seasonal water-flow, hydropower generation is usually deemed infeasible. Despite not having continuously running rivers; Saudi Arabia is one of the richest countries in the region in rain water with hundreds of dams holding billions of cubic meters of water behind them. Nevertheless, to date, there is not a single dam that is used for hydropower generation in the Kingdom. This paper explores this missed opportunity by showing the practicality of generating electricity even from low and seasonal water dams. It presents examples of installed hydropower plants in the region and lists possible locations of candidate dams to install small hydropower plants in the Kingdom. Preliminary estimates of the available hydroelectricity generation from the recommended sites are also presented

Keywords: *Hydropower generation, Seasonal-Water dams, Small Hydropower, Renewable energy, Saudi Arabia*

1. Introduction

Hydropower generation is one of the oldest methods known to mankind to generate energy. Whether mechanical or electrical, energy generated from running water has been attractive to people for its ease of harnessing, abundance, and availability. Generating electricity from hydropower plants has been known to be used since the late 19th century to power homes and commercial customers in many places around the world [1-4]. However, water turbines were invented in the early 19th century. Namely, the Fourneyron turbine was invented in 1827 by a French engineer named Benoit Fourneyron; and in 1849, the Francis turbine, which is the most widely-used water turbine, was invented by the British–American engineer James Francis. Later on, an American inventor, named Lester Allan Pelton patented the Pelton wheel in 1880. And lastly, the Kaplan turbine, which is an adjustable blades propeller turbine, was developed in 1913 by an Austrian professor named Viktor Kaplan [4].

1.1. Types of Hydropower Generation Plants

Hydropower generation can be classified in different ways; but the most common classification is based on the structure of the plant and type of energy generation [5,6].

The first type is the *Impoundment Plant*, which is based on a Dam creating a reservoir of water at a high elevation behind it. The difference in height between the stored and released waters creates an impoundment force that can generate up to megawatts of electricity depending on the size of turbines and generators used.

The second common type of hydropower generation is called *Run-of-River*, and includes the *Diversion* type plants. This type mainly depends on the mechanical power of the running water and strong currents of rivers to convert it to electricity without the need for a dam, and with little storage or none at all. Although they are easier and more convenient to install; however, the electricity generation capacities of run-of-river and diversion plants are usually much less than the capacities of impoundment hydroelectric plants [5].

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Another type of hydropower plants is called *Pumped Storage*, which has dual direction of water flow. Pumps are used to return the water back behind the dam when the power demand is low in order to increase the output power later when the demand for it is higher [5,6].
Impoundment type water dams are more attractive for hydropower generation than running streams since they add three more important features: steadiness in output power level, continuity in supply, and controllability. The main source of energy in impoundment plants is the water height, which is controllable; while the main source of energy in run-of-river and diversion plants is the speed of running water, which is usually variable and unpredictable. Because of the steadiness in high rainfall areas, hydropower generation from impoundment water dams can be used as base or peaking generation of electricity. The same applies to some diversion and run-of-river plants with storage reservoirs. While the hydropower generated from no-storage run-of-river and diversion plants is intermittent and mainly supplements other sources of electricity. The intermittency can be resolved and the electricity generation can be enhanced by the use of hybrid installations of combined PV solar or wind and hydro.
Many countries around the world depend on hydropower plants for their essential electricity generation. Brazil and China have some of the largest hydropower plants in the world. The tallest hydropower dam is the Jinping-I Dam in China, standing at 305m height (1001ft) [7]. In terms of generation capacities, China has the largest impoundment hydropower plants, with Three Gorges Dam at 22.5GW and Xiluodu Dam at 13.8GW installed capacities; and Brazil and Paraguay have the Itaipu dam, the second largest impoundment hydropower plant at 14 GW installed capacity [5]. Brazil also has the largest run-of-river hydropower plant in the world in Jirau at 3.75GW installed capacity [8]. As for pumped storage hydropower, China is building the largest plant at the Fengning Pumped Storage Power Station, with 3.6GW installed capacity [9]; and the USA has the second largest plant, the Bath County Pumped Storage Station, at 3GW installed capacity [10].

Another way of classifying hydropower plants is based on the size of the installed generation capacity [11]. Large hydropower plants are those having more than 30MW of installed generation capacity; while small hydropower plants, SHP have installed generation capacities ranging from 100kW to 30MW. Plants have capacities between 5kW and 100kW are called Micro Hydropower plants, MHP. There are also some applications that use mini plants, smaller than 5kW in size, and are called pico hydropower generation. Large plants, SHP, and MHP can all be used with a grid connection; while pico-generation is suitable for off-grid stand-alone applications, such as remote homes and farms.

Hydropower generation is one of the most well-established and wide-spread methods of generating electricity. It is important to note that the significance of hydropower generation is valid even in areas of low-current streams or seasonal water flow. Many countries around the world understand the value of running water, whether high or low, fast or slow, and make use of it to generate electricity even at the small kW plant size [12]. SHP and MHP are very common in places with low speed streams. It is very important to spread this concept around and bring it to the attention of law-makers and energy generation and regulation entities to utilize rain water and dams for power generation in Saudi Arabia, and the Middle East in general. For every day, hundreds of millions of cubic meters of water flow in streams and from dams in the region without being utilized for electricity generation.

2. Overview of Water and Dams in Saudi Arabia

Saudi Arabia occupies most of the Arabian Peninsula, with topographies ranging from Mountains and valleys, to sandy and rocky deserts, with scattered salt pans and lava areas. Geographically, the Kingdom can be divided into two major zones; the Sarawat Mountains and Najd Plateau. The Sarawat Mountains cover most of the rain-fed highlands of the western and southwestern regions; and the Najd Plateau composes of the vast arid and extra arid lands of the interior[13].
Saudi Arabia has mostly dry weather conditions, with little precipitation in the Kingdom that is unpredictable and irregular. The southwest part receives the highest amount of precipitation of Saudi Arabia, followed by the western region. In the southwest, the average annual precipitation can range from 100mm to more than 600mm on the mountains, making it the most important area in the country in terms of renewable water resources [14].
However, compared to other countries in the region, the Kingdom's annual precipitation is more than twice as much as the collective precipitation of Egypt, Tunisia, and Lebanon, combined. Unfortunately, the utilized rainwater in the Kingdom does not exceed 10% of its annual precipitation [15].
The main sources of fresh water in Saudi Arabia are seawater desalination plants and water treatment plants at dams and underground wells [16]. In 2014, around 2.8 Billion m^3 of fresh water was distributed in the Kingdom, of which 59% came from desalinated seawater and 41% came from treated water of dams and wells [17]. Therefore, water dams play a significant role in providing the water need of the population.

2.1. Dams in Saudi Arabia

The Ikrimah dam in Taif, was the first dam in the western region of Saudi Arabia. Built in 1956, the 11m high and 290m long dam was used for underground water recharge, with a storage capacity of half-a-Million cubic meters. Since then, many more dams were constructed around the Kingdom and over a period of fifty years, in 2006, there were 230 dams operating in twelve regions, with heights ranging from as low as 3m to as high as 106m [18]. In 2014, the number of completed dams more than doubled to 482 throughout the regions [17], 6 of which having heights above 73m; and 51 more *large dams* having heights over 15m (as per the International Commission on Large Dams ICOLD classification [19]). The average height of the total 57 large dams is 28m. There are also 52 more dams under construction, ten of them are large dams, which will bring the total number of dams in the Kingdom to 534, of which 61 are large dams.
In terms of storage capacities, in 2014, the Kingdom's 482 dams had combined capacities of 2.08 Billion cubic meters. This will be increased to over 2.5 Billion cubic meters with the additional 52 dams under construction. Figure 1 shows the progression of the number of dams in the kingdom and their designed storage capacities over the last decade [15,17].
Dams in Saudi Arabia can be classified based on their construction into four types; namely, concrete, earth-fill, rock-fill, and underground dams. In terms of objective, they can be classified into the following [18]:
Recharge underground water in the dam area to provide wells with water for the regions behind the dam.
Control flood water to protect cities and villages from the risks of torrents and flood dangers.
Secure *potable* water for the regions around the dam by supplying treatment plants with the stored water.
Secure *irrigation* water for farming and agriculture regions around the dam by supplying the stored water as needed.

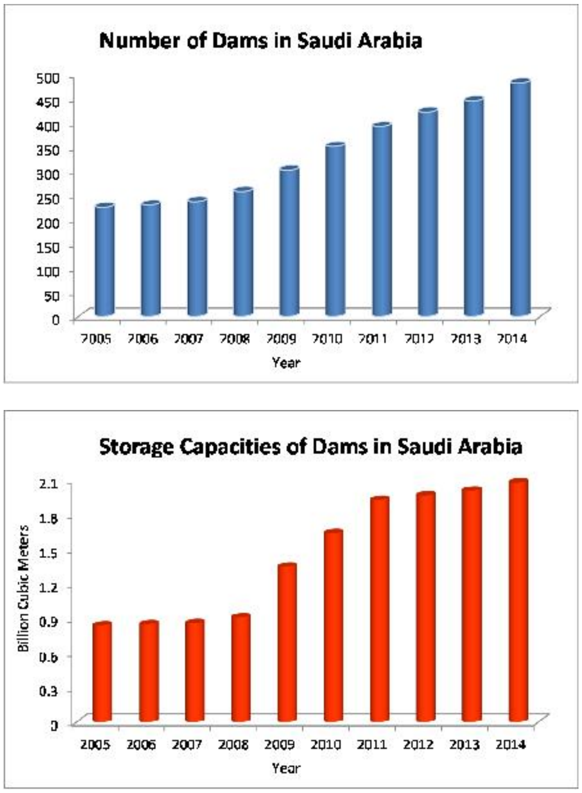

Fig. 1. Progression of dams in the kingdom and their capacities.

Table 1 shows the classification of the current built dams in the kingdom in terms of their objectives, along with their designed capacities. It can be seen from the table that while the vast majority of dams are constructed for recharging underground water; however, in terms of storage capacity, the largest capacities are associated with flooding control dams.

Table1: Types of dams in the kingdom in terms of objective.

Dam Type	capacity (m^3)	Count
Recharge	683,718,995	329
Control	892,434,027	92
Potable	456,219,786	59
Irrigation	51,500,000	2
Totals	**2,083,872,808**	**482**

Next to the Aswan High Dam in Egypt (111m), Saudi Arabia has some of the largest dams in the region. The King Fahd dam in the Bishah Valley rises at 103m with a storage capacity of 325 Million cubic meters, and a length of 507m. Compared to King Talal dam of Jordan at 106m height and 78 Million cubic meters capacity; the Wadi Baish dam in Jazan also rises 106m but with a capacity of 194 Million cubic meters, more than double the storage capacity of King Talal dam. Figure 2 shows charts of the largest six dams in Saudi Arabia along with their storage capacities [20].

Figure 3 shows a photo of Wadi Baish dam in Jazan when it overflowed in July 2011 due to heavy rain in the region (courtesy of AlRiyadh newspaper). And Figure 4 shows pictures of some of the largest dams in the Kingdom (*Courtesy of Google Pictures*).

In spite of the large number of dams in the Kingdome and the abundance of water storage in the reservoirs behind them; however, not a single hydropower plant of any size is built at any of the dams or the running rainwater streams that supply them. It is quite disappointing to see all these Millions of cubic meters of water just flow every day, carrying significant amounts of mechanical energy without being harvested and converted to useful electricity. It is important to realize that even the little amounts of electricity that could be generated from hydropower plants would be useful in lowering the burden on the electricity grid, conserving the country's resources, and saving the environment from harmful exhausts.

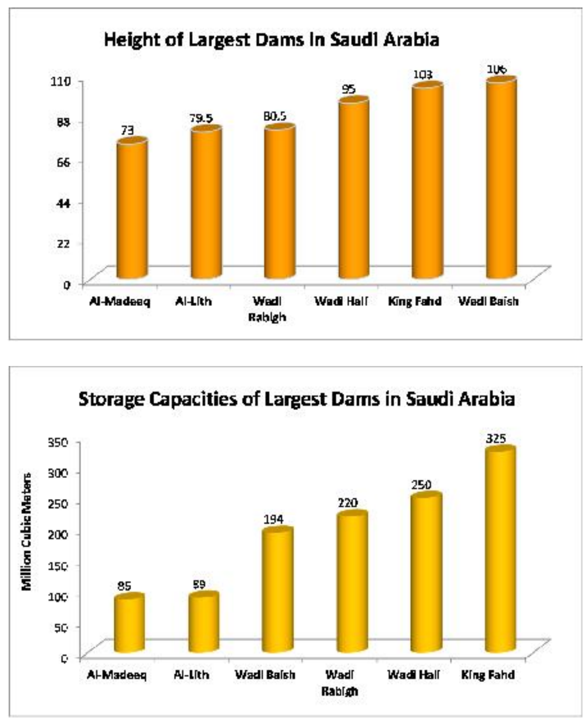

Fig. 2. Largest dams in the kingdom and their capacities.

Fig. 3. Overflow of Wadi Baish dam.

Fig. 4. Photos: Some of Largest Dams in the Kingdom.

3. The King Talal Dam Experience

King Talal Dam is located across the Zarqa River in Jerash, Jordan, about 60km NW of Amman. It was completed In 1978 with an initial height of 92.5m to secure irrigation water in the Jordan Valley by storing rainwater for later use. In 1988, a four year project was completed to raise the dam height to 106m to meet the country's increased water demand [21]. Figure 5 shows an aerial view of the dam and lake. The reservoir behind the dam has an 86 Million cubic meter designed storage capacity, with an active capacity of 78 Million cubic meters. Every year, about 17,000 hectares of farmland is irrigated by the water stored in the dam and around 120,000 people benefit from it. The dam is operated and managed by the Jordan Valley Authority.

2.1. Hydropower Plant at the Dam

In addition to storing and securing irrigation water, the King Talal dam plays an important role in generating electricity from the installed small hydropower plant. Two Francis turbines spin two 3MW generators for a total installed capacity of 6MW [21]. The generated electricity is bought by the Jordanian National Electric Power Company, NEPCO from the Jordan Valley Authority, JVA, and pumped in the electricity grid. Per NEPCO's records [22], the average amount of electricity purchased every year is around 14GWh. Over the past 18 years, the amount of electricity purchased by NEPCO ranged from as little as 7GWh in 2001 to as high as 17GWh in 2014. Figure 6 shows a graph of the amounts of electricity purchased from the hydropower plant every year since 1998.

Fig. 5. King Talal Dam and Lake in Jordan.

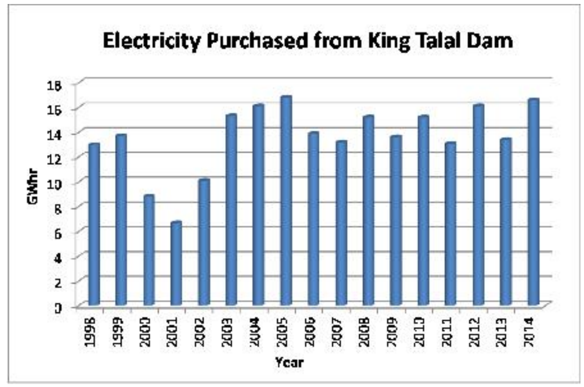

Fig. 6. Yearly electricity purchase by NEPCO from JVA.

It is important to note that the amount of electricity purchased does not necessarily account for the total amount generated by the hydropower plant; but rather indicates only how much electricity was pumped in the grid and paid for by the electricity company. For example, in 2011 and 2012, the International Energy Agency, IEA reported 55GWh and 61GWh, respectively, as the amount of electricity generated by Jordan's hydropower plant [23]. On the other hand, in the same years 2011 and 2012, NEPCO purchased only 13.1GWh and 16.1GWh, respectively, as shown in Figure 6.

Over 25 years now, the King Talal dam has proven to be a great model for small hydropower generation in the Middle East. It has shown that significant amounts of electricity can be generated from hydropower plants even in the case where no permanent surface water is available. Since it began operation, the King Talal dam hydropower plant sold a net of about 380GWh to the electricity company in Jordan.

Recently, there has been studies and recommendations by the government to extend hydropower generation to more dams in Jordan and expand the hydropower plants capacity to 33MW in current operational dams; in addition to 12MW more in future dams, bringing the overall installed hydropower capacities to over 50MW [24].

4. Possible Scenarios for Small Hydropower Generation in Saudi Arabia

With the amount of rainwater that falls on the Kingdom, and the hundreds of millions of cubic meters of water acquired by the many dams constructed throughout the country; several scenarios can be proposed to install small or even micro hydropower plants to harvest as much energy as possible and convert it to electricity. Given the stated examples, even large hydropower plants can be built on dams in Saudi Arabia to generate more electricity when needed and increase the installed power capacity in the Kingdom. Hydropower plants can be used as part of the power system for base or peaking generation. They can also be used as stand-alone power sources for remote and off-grid locations; or they can be merely used to supplement other sources of electricity and save fuel. Following are some of the possible scenarios to implement hydropower and benefit from water power in the Kingdom.

4.1. Hydropower Generation Based on Water Demand

In this strategy, the focus is on water demand, and electricity generation is a byproduct of the process. The main advantage of this scenario is to conserve the valuable oil resources of the

Kingdom. Most potable and irrigation water dams dispense water based on demand schedules or needs. Therefore, in this strategy, whenever water is needed from the dam, electricity is generated, replacing the equivalent amount of fuel that would have been burnt. In this case, electricity generation schedules could be predicted based on known water demand schedules. However, the drawback of this scenario is that electricity generation might coincide with low-electricity demand times, where it becomes redundant. Nevertheless, even in that case, saving oil resources by hydropower generation could still be viable and desirable since the plant is there anyways.

4.2. Controlled Water/Power Generation

This scenario is similar in its first part to the previous scenario, where electricity generation is a byproduct of water release. And its second part is the reverse of that, where water dispensing is the byproduct of electricity generation. In this strategy, whenever water is needed from the dam, electricity is generated, and whenever electricity is needed, water is released to generate electricity. There is a condition, however, to this strategy; that there should be no reason which restricts releasing the water from the dam when electricity is needed. Excess water release could be undesirable sometimes or even forbidden due to safety precautions or fear from flooding. Although, from the electricity side, this strategy could be very useful in meeting the power demand if the water is free to flow when needed. A good example is implementing this strategy in water dams used for recharging underground water wells in the regions around the dam. In this case, recharging can be done based on electricity demand, since recharging has less urgency than supplying potable and irrigation water, and can be scheduled in different times. Therefore, whenever electricity is needed, water would be released from the dam and used to recharge underground wells, creating a win-win situation.

4.3. Reverse (Pumped) Storage Generation

In order to overcome the drawback of releasing water when not needed as in the second scenario, reverse pumped storage can be used to restore the water back behind the dam after releasing it. Pumped storage has been well established for almost a century ago and is still being implemented in hydropower plants in many places around the world. Adding the pumped storage feature to the hydropower plant increases its controllability and makes its electricity supply steady and suitable for all uses of generation. It can be used as base generation in the power grid, or to offset or supplement other sources. It can also be used as a part of a peak shaving supply strategy to lower the burden of the power gird during peak demand times. The way pumped storage works is usually by creating a second pond or reservoir at the release side of the dam to collect the released water. This could be done by building a shorter dam not too far from the main dam, or as far as needed to create the required size of the reservoir. The water collected can then be pumped back to the original reservoir behind the main dam when the electricity demand is low, in order to store the water in the main reservoir for later use when the electricity demand is high. Such a system is not as difficult as thought to implement. The same penstock can be used for the bidirectional water flow. And the hydropower plant can have a dual-action system consisting of a reversible pump-turbine/motor-generator assembly, which can be used for both water flow directions. One significant drawback of pumped storage plants is that they consume electricity to pump the water back behind the dam. In Saudi Arabia, this means consuming the country's natural resources of oil and gas, since they are the main resources used for electricity generation. This defies the original objective of introducing hydropower in the Kingdom to conserve natural resources and not waste them.

4.4. Hybrid Solar or Wind Generation

An effective solution to avoid burning fuel to generate the electricity needed for hydropower plants with pumped storage is by using other renewable energy resources. A hybrid hydropower with PV solar or wind generation can form a better controlled plant that supplies consistent and steady power generation. On one hand, the PV or wind power can be used in the pumped storage process, conserving natural resources. And on the other hand, the hydropower generation can overcome the intermittency of the PV and wind outputs, creating another win-win situation. The hybrid installation can also be expanded to supply more power from the combined water/sun, or water/wind, or even water/sun/wind resources altogether, creating a well-balanced blend of electricity generation. One of the drawbacks of such installation is that it might need separate piping for the pumps and the turbines.

4.5. Generation from Running Water Streams

In addition to generating hydropower from water dams, running streams in Saudi Arabia have a great potential for more electricity generation. Many water streams flow in the Kingdom valleys. Some are constantly running, others are seasonal. Some run deep with strong flow, and others are shallow and weak. An example of a constantly running stream is the one in Wadi Hanifah near the capital, Riyadh, as the pictures show in Figure 7 (*Courtesy of Google Pictures*).

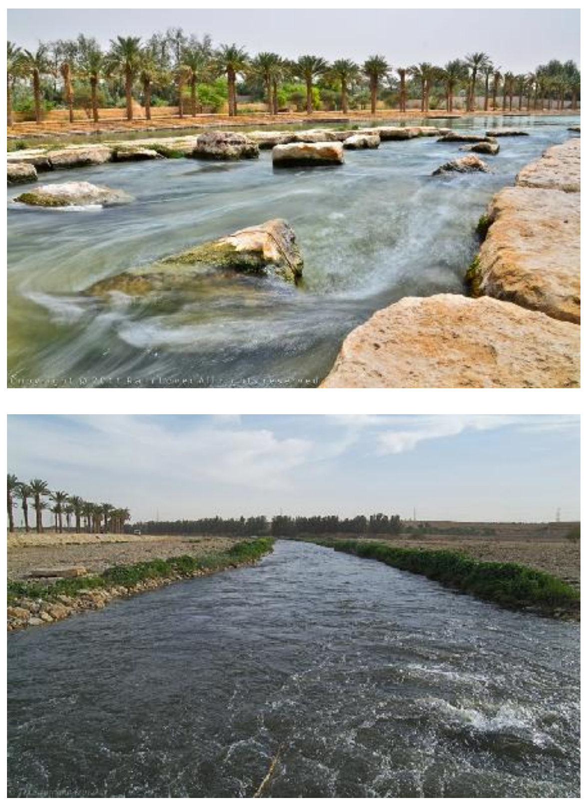

Fig. 7. Running water stream, Wadi Hanifah.

Wadi Hanifah is one of the longest in the Kingdom, extending for some 80km and with depths of more than 1.5m in some

areas. Such running water streams flow with a significant amount of mechanical energy that is attractive for installing SHP or even MHP for electricity generation.
In addition to running streams of the valleys, as it has been depicted in section 2, there are hundreds of small dams built throughout the kingdom with heights that are not significant enough to install impoundment type hydropower generation. Nevertheless, the water discharge from most of these dams create running streams that are suitable for run-of-river or diversion type hydro-generation.

4.5. Stand-Alone Off-Grid Generation

All four scenarios presented for hydropower generation were for power grid connection. However, they could work with an off-grid stand-alone setup as well to supply small nearby customers or water treatment plants and pumps. In most cases, villages and small towns are scattered in areas around dams and running streams and get their potable and irrigation water supply directly from dams and streams. Water treatment plants are also usually built near dams and streams to generate the needed water for people's use. These treatment plants require power to operate the systems and pumps. It makes perfect sense to supply these plants with the needed electricity directly from the water, instead of extending the power network grid to them or build small fuel-based plants for electricity generation. Moreover, since the dams already supply nearby villages with water, it is more economically feasible to supply the villages with electricity from the hydropower plants at the dams as well, especially that this power is readily available. Extending the power network grid is very costly, and the energy losses associated with transmitting electricity through the power lines are high. Similarly, the cost of transporting fuel to remote areas where diesel electricity generation plants are built is also considerably high and risky. Off-grid utilization of a hydropower plant in such cases is very useful and attractive. It is important to note that a hydropower plant with a power capacity of only one-Mega-Watt is sufficient to supply a small village with electricity. Depending on the continuity of electricity generation and the consumers' behavior, the single 1MW plant could supply as many as 1000 households.

5. Available Hydropower Generation Capacities

Based on the available information about the Kingdom's dams and reservoirs, and the daily water levels data, which was provided by the Ministry of Electricity and Water, preliminary hydroelectricity generation capacities from the recommended sites could be estimated. The following sections present these estimates in a brief manner for demonstration purpose only. More thorough investigation for each individual site is needed, which is beyond the scope of this work, in order to have more accurate estimates. Economical feasibility studies should also be carried out to examine the viability of such installations.

5.1. Hydropower Generation at the Six Largest Dams

As shown in Figure 2, there are six large dams in the Kingdom, with heights ranging from 73m to 106m; and storage capacities ranging from 86 to 325 Million cubic meters. Based on the data provided for these dams, SHP could be installed at these sites with capacity ranges as follows.

Wadi Baish Dam and King Fahd Dam can each comprise a SHP with a capacity range of 9-10MW. Wadi Hali Dam can comprise a SHP with a capacity range of 8-9MW. Wadi Rabigh Dam and Al-Lith Dam can each comprise a SHP with a capacity range of 7-8MW. And Al-Madeeq Dam can comprise a SHP with a capacity range of 5-6MW. Hence, the total estimated capacities to be installed at all six dams is in the range of 45-51MW. Assuming 50% operation at peak installation, these plants would generate electricity at an average of 210GWh per year. This is at least 15 times more than the average electricity generation of King Talal Dam in Jordan.

5.2. Additional Generation at the other 51 Large Dams

In section 2.1, it was depicted that there are 51 large dams in the Kingdom with heights of more than 15m. These dams are also great candidates for SHP installations. Although the capacities would be much less than those of the six largest dams, however, adding the capacities of all 51 plants would show the significance of such installations. Dividing the dams in range of heights, there are 7 dams 30-40m tall, where 3MW SHP can be installed at each. There are 17 dams that are 20-27m tall, where 2MW SHP can be installed at each. And the remaining 27 dams have heights between 15m and 18m, where a SHP of 1MW capacity can be installed at each. The estimated total power capacity of all these installations is 82MW, which is 70% more than the total power capacity of the six largest dams combined. Assuming 50% operation at peak installation, the plants at the 51 large dams would generate electricity at an average of 360GWh per year.

5.3. Hydropower Generation from Running Water Streams

There are 482 water dams currently installed in the Kingdom, 57 of them are large dams with heights over 15m tall, and the other 425 have heights between 3m and 14.5m. Although it is not as feasible to install impoundment type hydropower generation at these dams as it is for large dams; however, most of these dams generate strong running streams from the discharged water. Therefore, run-of-river or diversion type hydropower generation becomes attractive in these locations. In addition, more power generation can be installed along the tens of running streams in the Kingdom, like the ones depicted in section 4.5.

The estimated hydropower generation capacities that can be installed at the 425 dam sites can range from MHP of as little as 20kW to SHP of as high as 500kW. Thus, the average installation capacity at each site would be in the range of 80kW, which brings the total installation to about 34MW, and would generate electricity at an average of 150GWh per year.
The scattered SHP and MHP installations on running streams would add another 6MW of power capacity, which would generate an average of 25GWh of additional electricity per year.

5.4. Penetration Percentage

Adding all possible capacities, the total estimated hydropower generation capacity that can be installed in the Kingdom would be around 170MW. The estimated total yearly electricity generation from all these sites would be around 745GWh. Although this would not penetrate the network with more than 0.5% of the total installed power capacity in the Kingdome; however, given the scattered distribution of these plants, each plant would be significant and effective in providing electricity when compared to other power installations within its vicinity.

4. Conclusion

Although proven effective, hydropower generation is usually overlooked and undermined in Saudi Arabia. The country is rich in rainwater and stored water capacities behind hundreds of dams, which could be a good renewable energy source of electricity. In rural areas around these dams, hydropower plants could be the main source of energy to supply villages with electricity from the dams as well as water. The estimates show that the Kingdom can install combined capacities of at least 170MW of hydropower at existing dams and streams, generating around 745GWh of electricity every year. Although this does not compare to 4GW and 8GW oil-fired plants; however, it is time to realize that even the little amounts of electricity that could be generated from hydropower plants would be very useful. It can lower the burden on the electricity grid, conserve the country's natural resources, and save the environment from harmful exhausts. Further feasibility studies and economical analysis are required to support the recommendations of this work.

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