Asian Journal of Water, Environment and Pollution, Vol. 20, No. 2 (2023), pp. 9-15.
DOI 10.3233/AJW230019

Optimisation of Reverse-Osmosis Water Purification Plant Powered by Hydro-Generators at the Dead Sea

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Received May 13, 2022; revised and accepted August 23, 2022

Abstract: With the Jordan River as its main tributary, the Dead Sea is a hyper-saline lake, which was formed around 140 centuries ago. Climate change used to be the principal driver of water level changes. However, anthropogenic activities have recently emerged as a prominent source of excessive depletion. This study provides a realistic strategy for desalinating the Red Sea water whilst generating electrical power for the Dead Sea conveyance project. Seawater from the Gulf of Aqaba is transformed into highly concentrated saline water flowing to the Dead Sea whilst delivering purified drinking water to nearby regions using reverse osmosis plants. Being an energy-intensive process, a series of hydro-generators with efficient energy recovery devices will minimise the running cost by half.

Key words: Reverse osmosis, hydro-power, conveyance project, Dead Sea, desalination.

Introduction

At 425 meters below sea-level, the Dead Sea shore is the lowest land-based elevation on earth. The lake's deepest point is 730 meters below sea-level, making it the world's deepest terrestrial location (Malkawi et al., 2016; Markle et al., 2013). Flooding rainwater from adjacent mountains with the Jordan River's flow accumulated in the lake over the past centuries. Due to high temperatures, air pressure, and evaporation, the lake became one of the saltiest bodies of water on the planet, with a salinity of 342 g/kg, or 34.2 % (in 2011) (Markle et al., 2013). Such properties spurred numerous chemical enterprises to employ evaporation ponds to extract precious compounds like potash. Consequently, the Dead Sea water level is receding at a sharp rate of more than 1 meter per year, with a current surface area of 605 km^2 compared to 1,050 km^2 back in 1930 (Markle et al., 2013; Raghukumar, 2012). To sustain its present size, The Dead Sea requires an annual infusion of 160 billion gallons of water (Khodayar and Johannes, 2020). Another key factor influencing the rapid drop of water level in the Dead Sea during the last few decades is the drop in the amount of runoff water flowing into the Dead Sea during the winter months and direct evaporation from the lake's surface due to high temperatures. Located within one of the most water-scarce regions on earth, combined with urban sprawl at the expense of green areas aggravated the issue (Khodayar and Johannes, 2020). According to Jordan's Water Ministry, rainfall was below normal in volume in eight of the ten years from 2004 to 2014, depleting rivers and aquifers relying on it.

Such a plummet is leading to catastrophic social, economical, environmental and biological implications and consequences. Currently, there is more than 5000 staff working in the tourism sector in the Dead Sea area, more than 80 hotels and resorts, and more than 2 million tourists visiting the attraction spot annually. Hundreds of sinkholes have been forming along the Dead Sea's shoreline (Abelson et al., 2003), exposing damage to the surrounding infrastructure, including roads and bridges (Gavrieli et al., 2011). Figure 1 illustrates satellite images depicting water level changes since 1972.

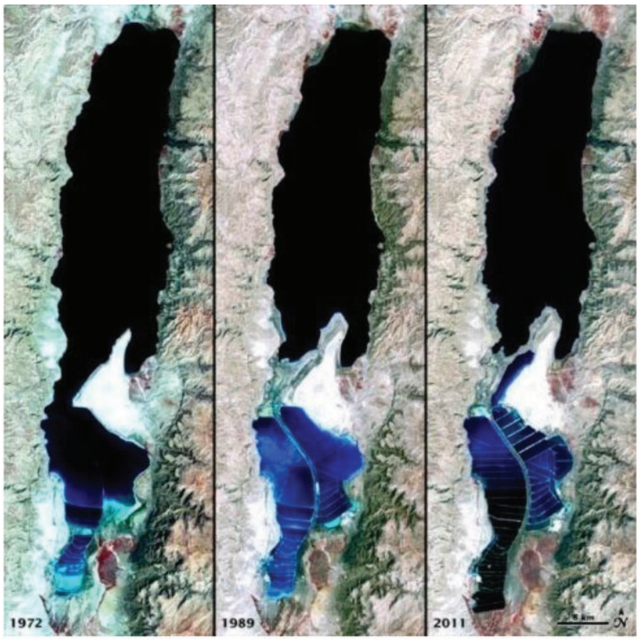

Figure 1: Water level changes in the Dead Sea (Fawzi and Mousa, 2021).

Several canal and pipeline plans have been previously proposed to aid the lake's recovery and aim to find common ground for the world's most water-scarce area. The Red Sea–Dead Sea Water Conveyance Pipeline project is one of these projects that aims to deliver water to neighbouring countries whilst transporting brine to the Dead Sea to stabilise its water level (Gavrieli et al., 2005). The planned conveyance is planned to pump seawater 230 meters uphill from the Gulf of Aqaba in the Red Sea into Jordan's Valley. The water would then flow via gravity through several pipes to the Dead Sea region, and ultimately to the lake's body. The project is expected to need around 225 kilometers of seawater and brine pipes. An additional 178 kilometers of freshwater pipes would be installed in the Amman region as part of the project. Several water desalination plants and at least one hydropower plant would also be included. The project would produce roughly 850 million cubic meters of freshwater in its ultimate phase. Depending on the structure and phases of the project, cost estimates range from 2 to more than 10 billion dollars. This imposes a major challenge to the surrounding countries' economies. Moreover, electrical power from Jordan's power system would be required for the project (Gavrieli et al., 2005, Khlaifat et al., 2020). Pumps and desalination plants consume heavy power which is not included in the project cost. A modified structure of the conveyance project with the integration of efficient energy recovery devices and a series of high-efficiency hydro-generators is proposed. Runtime energy consumption, including pumps, water conveyance, and the pre- and post-treatment activities can be reduced by 50%. Section: Reverse osmosis introduces the concept of reverse osmosis plants. The proposed system structure and components are discussed in Section: Proposed System. Section: Conclusion explains the study and presents future work upon the implementation of the project.

Reverse Osmosis

Osmosis is one of the most essential naturally occurring phenomenon. During this process, a weaker, low dense, saline solution will prefer to move to a stronger, higher dense, saline solution through a permeable membrane. Figure 2 illustrates the natural process of osmosis.

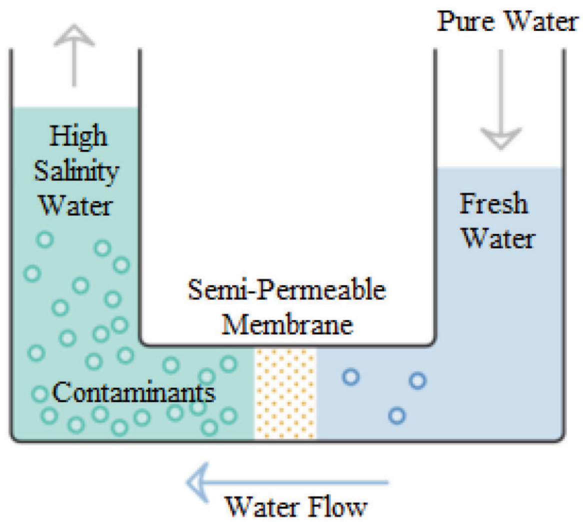

Figure 2: Osmosis process.

Reverse osmosis (RO) is a water purification method that separates ions, undesirable compounds, and bigger particles from drinking water using a partly permeable membrane. Applied pressure is utilised to counteract the osmotic pressure. Reverse osmosis is considered the leading and the most optimized membrane-based desalination process that is currently dominating the desalination market. The cost of a RO system varies significantly depending on the flow-rate and level of pre-treatment required. A small RO system with a capacity of 20 to 40 LPM might cost less than $60,000, while a larger 1100 LPM system with a complicated pre-treatment system could cost $2 to $4 million. At the high end, a 7500 LMP highly advanced system can cost up to $10 million (Jafari et al., 2021; Sawaki and Cheng-Liang, 2021).

The primary impediment to the wide deployment of seawater reverse osmosis is its high specific energy consumption. While conventional surface water treatment uses between 0.2 and 0.4 kWh/m^3, the theoretical minimum specific energy for seawater desalination (total dissolved solids (TDS) = 35,000 mg/L) is 1.07 kWh/m^3 for 50 percent recovery (Voutchkov, 2018). This means that for every 1 liter of freshwater, 1 liter of high salinity brine will be produced. Furthermore, the system requires a significant amount of additional energy to operate. The specific energy consumption of the seawater reverse osmosis process has been reported to be 2.5–4.0 kWh/m^3, which is much greater than the method's minimal specific energy. A real-scale seawater reverse osmosis plant's specific energy consumption is significantly higher, at around 3.5–4.5 kWh/m^3 including pre- and post-treatment activities (Kim et al., 2019). Seawater is not often used over regular surface water because of the high energy demand for the reverse osmosis desalination process. In this study, an average of 4 kWh/m^3 consumption is assumed including the pre- and post-treatment activities. However, the power demand will drop after minimising several design and operation aspects.

Despite its high power consumption, the use of seawater reverse osmosis technology for drinkable water production is imperative in certain places at which seawater is the sole available supply of water. Due to the common water scarcity issue in the Middle East and North Africa (MENA), reverse osmosis is becoming a popular choice for water production. Desalination is becoming increasingly important in these areas as water demand rises (Kim et al., 2019). Desalinated water is utilised not only for drinking but also for agriculture and industry (Kim et al., 2019, Werber et al., 2016). Reverse osmosis projects has recently been seen in areas outside of the MENA to meet demand induced by limited surface water sources owing to drought. The security of currently accessible water supplies, according to studies, will not be stabilized in the future (Ramanathan and Feng, 2009). As a result, in this new period of water scarcity, many nations will place a strong emphasis on saltwater desalination to produce freshwater. Figure 3 illustrates a typical reverse osmosis desalination process. Since granules and solids might cause clogging the surface of the reverse osmosis membrane, a pre-treatment stage is used to remove contaminants prior to the reverse osmosis process. High-pressure pumps (HPP) are used to overcome the osmotic pressure of seawater to initiate the reverse osmosis process. Such high-pressure would result in a high specific energy consumption (Kim et al., 2019). A high-efficiency energy recovery device (ERD) along with a booster pump (BP) are used to extract the maximum energy from the system. Plants with efficient ERD utilize significantly less energy than plants with a low-efficiency ERD.

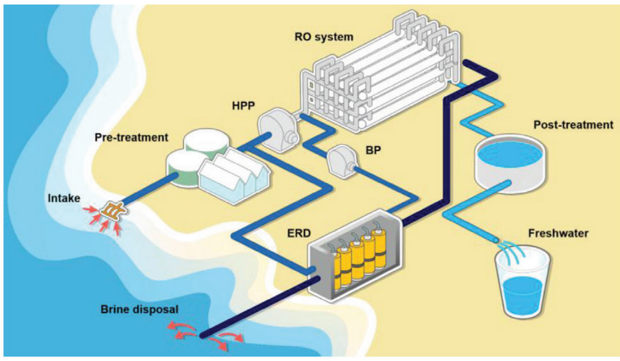

Figure 3: Basic structure of reverse osmosis plant (Kim et al., 2019).

Energy consumption is influenced by all components in the RO system. Despite its minor impact, pre-treatment, which is typically accomplished by granular filtration, can account for around 11% of the overall energy consumption (Kim et al., 2019; Voutchkov, 2018). Furthermore, the seawater's properties including salinity and temperature affect the minimum power required to separate water in reverse osmosis. Although the RO system is the most energy-intensive process in the plant (about 71%), the efficiencies of the HPP, BP, and ERD have a substantial impact on overall energy consumption (Kim et al., 2019; Voutchkov, 2018). The isobaric Dual Work Exchanger Energy Recovery (DWEER) is the most efficient energy recovery device (ERD) currently created. It was first introduced in the 1990s by DWEER Bermuda and licensed by Calder AG (Huang et al., 2020; Yadav and Md, 2021). It can recover up to 98 % of the energy in the brine waste stream, which is then utilised to pressurize raw water and minimise the energy input for high-pressure feed pumps by 60%. The DWEER system captures and transfers energy wasted in the reject brine stream using a piston double-chamber reciprocating hydraulically powered pump and a proprietary LinX valve system. The high-pressure pump does not need to be connected to the energy recovery device with the DWEER. This allows for the employment of fewer, but more powerful, pumps. Figure 4 shows the basic operation of the DWEER.

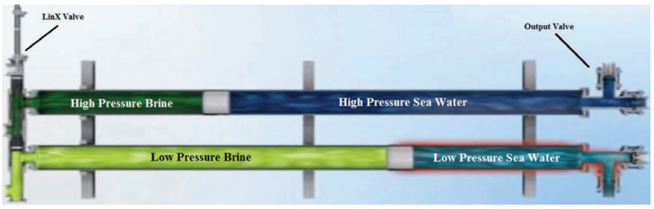

Figure 4: Basic DWEER system structure.

As seen in Figure 4, high-pressure brine from the RO membranes enters the LinX valve and is directed by its piston into vessel 1 which is already filled with low-pressure seawater. In the vessel, the pressure of the brine is transferred to the seawater. The highly pressurized seawater then exits the DWEER through the output valve. From there, the seawater is routed to the high-pressure membrane feed stream via a booster pump. Simultaneously, low-pressure seawater is introduced into vessel 2 which contains low-pressure brine. As the seawater fills the vessel, the low-pressure brine is discharged through the LinX valve. Afterwards, the LinX valve actuates and the process repeats itself and the introduction of DWEER reduced the total specific energy consumption by about 5%. Being the world's deepest terrestrial location, the dead sea can have water flowing via gravitational force from surrounding areas. Such property has the potential of generating more power to minimise the heavy load of the RO process even further.

Proposed System

Being amongst the world's most water-scarce areas, Jordan is aiming to produce 850 million cubic meters of freshwater annually from this project to cover its extreme shortage in drinking water, agricultural, and industrial needs. This roughly translates to 27 m^3/sec or about 97,000 m^3/h of fresh water. Having a 50% recovery rate (Kim et al., 2019; Voutchkov, 2018), the RO system will produce a similar 27,000 m^3/sec of high salinity brine which will flow into the Dead Sea. Such water volume will roughly require 388 MW average continuous electrical power assuming an average of 4 kWh/m^3 including the pre- and post-treatment activities is required. Jordan generates electricity from a variety of sources, the most common of which is natural gas. Currently, the Kingdom exports nearly all its gas and fuel needs and has an electrical generation capacity of about 4000 MW/h, while the Kingdom's peak consumption is about 3200-3100 MW/h (NEPCO, 2022). As a result, the RO desalination project will consume around 9.7% of the annual power generation. With the current increase in fuel prices, a major challenge is imposed on Jordan's economy and its power grid. The previously proposed conveyance would pump seawater 230 meters uphill from the Red Sea's Gulf of Aqaba through the Arabah Valley in Jordan. The Arabah Valley region is split into three divisions topographically. The terrain progressively rises about 77 kilometers (48 miles) north of the Gulf of Aqaba, reaching a height of 230 meters (750 feet) above sea level, which marks the watershed boundary between the Dead Sea and the Red Sea. The ground dips gradually northward over the following 74 kilometers (46 miles) to a location 15 kilometers (9.3 miles) south of the Dead Sea. Afterwards, at the last segment, The Arabah slopes steeply to the Dead Sea, which is 425 meters (1,394 feet) below sea level. Figure 5 illustrates the topographical elevation of the Dead Sea area. The original project proposes a water desalination facility and one hydro-generation plant near the Dead Sea utilising the free-running water.

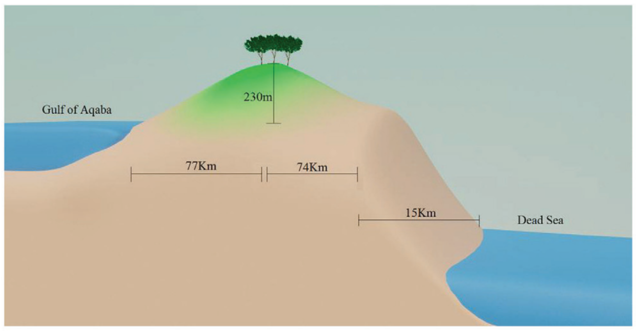

Figure 5: Topography of the Arabah Valley and the Dead Sea Area.

Figure 6 presents the proposed reverse osmosis desalination plant with hydro-generators for optimal operation. Using high-pressure pumps, seawater from the gulf of Aqaba will be pumped at a rate of 54 m^3/sec for 77 kilometers north, reaching a height of 230 meters above sea level. Afterwards, gravitational forces will allow water to flow 74 kilometers north into a reservoir.

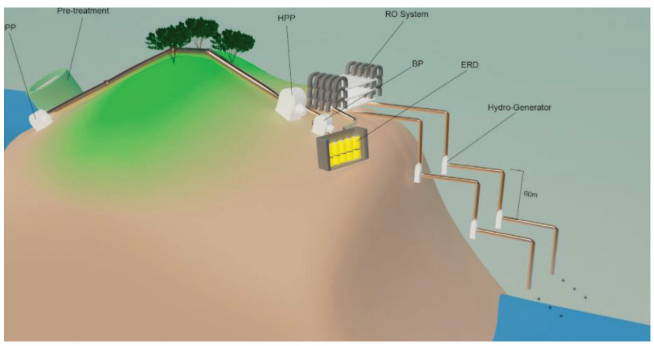

Figure 6: Proposed system structure and operation.

Seawater from the reservoir will be pumped at a rate of 54 m^3/sec via a second high-pressure pump into the reverse osmosis plant. A multilayered DWEER system will capture and transfer energy in the brine waste stream back to the system. This lowers the total energy needs by about 5%. Afterwards, fresh water and high salinity brine will flow at a rate of 27 m^3/sec into two pipes. The pipes' internal diameter is chosen to be 2 meters. The natural steep slope in the area's topography will deliver an excessive amount of energy to the free running water. Equation 1 shows the velocity of the free running water within the pipes.

$$v = \frac{Q_w}{3600\pi\left(\frac{d}{2}\right)^2} \tag{1}$$

where
d : Pipe Inner Diameter (m)
Q_w : Water Flow-Rate (m^3/h)
v : Water Velocity (m/s)

From equation 1, the fresh water's and the brine's velocity will be equal to 8.6 m/s. Afterwards, the flow will pass through a series of seven hydro-generators. Hydro-turbines convert energy from flowing water to the row of blades attached to a spinning shaft. This rotational motion is fed to a generator, which generates electricity. Turbines have various forms and sizes, each suited to a certain use (Casini, 2015). Each type of turbine is built to harvest the most energy possible for the environment in which it is used. Rentricity Flow-to-Wire (Casini, 2015; Pierce, 2012) offers hydro-generators for large scale applications (30 kW~20 MW). Such systems are usually customised to meet the existing pipe size required for the task. Figure 7 shows the basic structure of such hydro-generators.

The hydraulic head, which is the height and speed of the incoming water, and the hydroelectric discharge, which is the volume of water that flows are significant parameters for power generation. Further considerations can affect the use of hydro-generators like efficiency and cost (World Energy Council, 2013). Equation 2 shows the amount of power generated by a Hydro-generator.

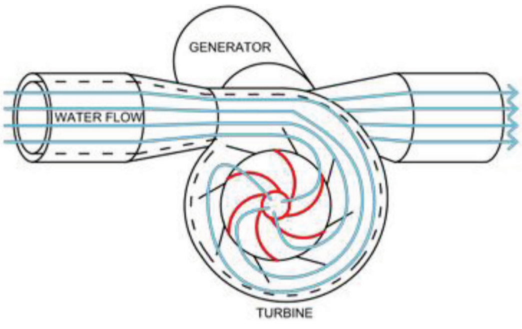

Figure 7: Hydro-generator basic structure (Casini, 2015).

$$P = m \times g \times H_{net} \times \eta \tag{2}$$

where:

P: Power, measured in Watts (W).

m: Mass flow-rate in kg/s (numerically the same as the flow-rate in liters/second since 1 liter of water weighs 1 kg)

g: Gravitational constant (9.81 m/s^2)

H_{net}: Net head. This is the gross head physically measured at the site, minus any head losses. usually, head losses are assumed to be 10%, so $H_{net} = H_{gross} \times 0.9$

η: Product of all component efficiencies. Normally, the turbine, drive system and generator.

In the majority of hydro-systems, the turbine efficiency is around 90%, the drive efficiency is about 98%, and generator efficiency is around 95%. Hence the overall system efficiency(η) can be calculated as in equation 3.

$$\eta = \eta_t \times \eta_d \times \eta = 0.9 \times 0.95 \times 0.98$$
$$= 0.838 = 83.8\% \tag{3}$$

where
n_t : Turbine efficiency
n_d : Drive efficiency
n_g : Generator efficiency

From equations 2 and 3 above, the hydro-power produced by each generator can be calculated as in equation 4.

$$\text{Power (W)} = m \times g \times H_{net} \times \eta$$
$$= 27{,}000 \times 9.81 \times (60 \times 0.9) \times 0.838$$
$$= 11{,}985{,}897 \text{ W} = 11.986 \text{ MW} \tag{4}$$

Having two pipes carrying fresh water and high-salinity brine, hydro-generators can be installed in both conduits doubling the amount of generated power. Therefore, the total amount of power generated by the overall system is 167.8 MW/h. As previously mentioned, using the stackable DWEER system would save 5% of the total amount of required operational power, while the power generation of the proposed series hydro-generators is equivalent to 45% of the remaining operational power. Hence, using the proposed system, the total amount of power required to produce an annual 850 million cubic meters of freshwater and a similar volume of brine is reduced by 50%.

It should be noted that specific energy consumption is influenced by several external factors. The temperature influences the apparent membrane characteristics, while the feed salinity affects the osmotic pressure of the feed. Therefore, desalination of highly salinity streams is inherently energy intensive. Equation 5 illustrates the parameters that affect the SEC.

$$SEC = \frac{R\widehat{G}(c_p) + (1-R)\widehat{G}(c_R) - \widehat{G}(c_p)}{R} \quad (5)$$

where

G: Specific Gibbs free energy as a function of composition at a fixed temperature and a fixed pressure.

c_P: Solute concentrations in the product stream

c_R: Solute concentrations in the retentate stream

R: Water recovery ratio

C_R can be further described as in equation 6

$$C_R = \frac{C_F}{(1-R)} \quad (6)$$

where

c_F: Salinity of the feed stream

R: Water recovery ratio

Because of its salinity dependence, SEC is high for hyper-saline brines (Davenport et al., 2018). Furthermore, the water permeability coefficient (A) and the salt permeability coefficient (B) of the RO membrane both increase when the water temperature rises (Kim et al., 2019). The SEC is minimised because water production with a high A value requires low hydraulic pressure. Furthermore, when the temperature rises, the minimum energy needed for separation increases resulting in an increase in SEC. Because the increase in A has a greater impact on the SEC than the increase in minimum energy, the SEC of the RO system decreases as the temperature rises (Ammous and Maher, 2014). Due to the soaring high temperatures and air pressure in the Dead Sea region. Figure 8 illustrates the relationship between temperature and the total energy consumption for typical RO systems including the pre- and post-treatment activities.

With surface temperatures approaching 36°C under shade during the summer diurnal cycle, temperatures in the Dead Sea area can exceed 50°C during summer under direct sunlight (Nehorai et al., 2009). Such soaring high temperatures combined with high humidity will significantly improve the overall energy consumption figures. Further reduction in the SEC can be measured once the project is implemented.

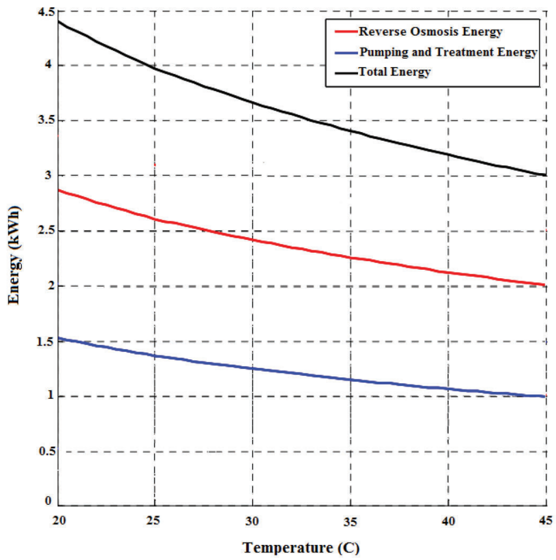

Figure 8: Relation between total energy consumption by reverse osmosis and temperature.

Conclusion

The design and development of energy recovery devices for seawater desalination systems are relatively advanced. Therefore, previous projects that were aimed at the recovery of the Dead Sea can be efficiently implemented. The reconfiguration of the components of the water conveyance project linking the Gulf of Aqaba with the Dead Sea can immensely reduce the running energy costs. By utilising the DWEER system for energy recovery, and the implementation of 14 hydro-generators within the project pipes, the running energy costs of the project can be reduced by 50%. Such reduction is vital to the low-income, water-scarce countries of the MENA region. Furthermore, further reduction in energy consumption can be anticipated due to the high temperatures of the geographical location of the project.

Conflict of Interest

The author states that there is no conflict of interest.

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Asian Journal of Water, Environment and Pollution

Volume 19 Number 3 **May, 2022**

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