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Recovering energy by hydro-turbines application in water transmission pipelines: A case study west of Saudi Arabia

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A B S T R A C T

Pressurized water transmission lines reserve amounts of energy that are dissipated by pressure control devices. The dissipated energy may be recovered by installing hydro-turbines at high pressure points and benefit from power production and decreasing CO_2 emissions. In this work, an existing transmission water pipe was simulated under several velocity scenarios, and results indicated that an extensive amount of energy can be recovered by installing Pelton turbines. The approach began by identifying the location of the residual pressure in the system and quantifying the amount of power to be harvested. Afterwards, the pipeline was redesigned by changing the allowed velocity from 1 to 2.5 m/s consecutively. Moreover, the best fitting turbine was selected at each of the residual pressure locations and outputted the potential amount of power to be produced. Finally, a financial and environmental evaluation of the presented solution was conducted. Based on this methodology, the total system cost was reduced by 2.74% because of adopting the maximum allowable velocity of 2 m/s. System optimization allowed for the installation of hydro-power plants with total capacity of 5,751 kW and energy payback period of 9.46 years. Moreover, a reduction in carbon footprint was estimated by 35,295t of CO_2 per year.

1. Introduction

The kinetic energy in pipelines is considered as a renewable source of energy by taking advantage of the residual pressure available in the energy dissipating devices, such as pressure and flow control valves along the water system. Power generation is possible by adopting and introducing the proper hydroelectric technology such as hydro-turbines, hence the water management sector can be developed from being intensive and non-renewable to energy sustainable.

Conventional reaction turbines such as Kaplan, Propeller, Francis and Pump as Turbines (PATs) are designed for low head water systems. Even though Francis & PATs are generally able to handle higher heads than Kaplan turbines, the efficiency of these turbines tend to decrease when having a low flow condition [1]. As for conventional impulse turbines such as Pelton, Turgo, and Crossflow turbines, they are not usually recommended when there is a site that requires downstream pressure [2]. However due to their flat efficiency curve, conventional impulse turbines are highly recommended for sites with high variable flow. Nevertheless, impulse turbines are considered more costly than reaction turbines [2].

Several developments have been made on reaction turbines making them more economical for application and operation. For example, advanced Francis in-line turbine is now available for pipe diameters ranging from 4″ to 24”. This turbine is usually installed in parallel with pressure reducing valve and it can hold capacity up to 1 MW [2]. Moreover, Lucid Energy have manufactured a new generation of impulse in-conduit turbines, which can be installed directly at high pressure points of the pressurized system. This technology is offered for several pipe diameters ranging from 24″to 60″ and can generate power up to 100 kW per turbine with minimum flow ranging between 1 & 5.6 m^3/s [3].

A Study was done by Christine Power et al. [4] evaluating the method of energy recovery in wastewater treatment plants (WWTPs) by installing hydro-power turbines at the discharge points. The amount of power generated by installing the turbines have fluctuated from 3 kW to 234 kW based on the available flow rate and head at each WWTPs studied in UK & Ireland. Moreover,

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the feasibility of applying this kind of technology was conducted through sensitivity analysis. This was done to demonstrate the effect of seasonal flow variation, turbine selection, power cost and financial incentives on power generation and payback period. In the study, a method was developed to optimize the design flow to accommodate for flow variation without affecting the installed turbine efficiency. As a conclusion, the flow variations that were caused by demographic and climate change in the short and long term were found to be the governing variables affecting turbines selection and their efficiency.

Another study was conducted by J. García Morillo et al. [5] on Bembézar Margen Izquierda (BMI) irrigation district in south of Spain, where high potential points were located within the irrigation network. The irrigation network was simulated for several demand scenarios using hydraulic simulator program "EPANET". The results of the simulation showed that pump as turbines (PATs) and conventional Francis turbines were suitable to be installed at different locations of the network where substantial amount of energy can be recovered. Moreover, an economical evaluation was done for installing PATs and conventional turbines, and it was concluded that PATs are more economical than conventional turbines upon application on irrigation systems since there is low head and low flow rate. Moreover, adopting such technology could lead to significant reduction in carbon footprint of irrigated crops with an estimated reduction up to 108t of emitted carbon dioxide (eCO_2).

Pump as turbines application in irrigation networks was also under the microscope of Miguel Crespo Chacon et al. [6]. The study conducted a methodology for the selection of the right Pump as Turbine at each high-pressure point within the irrigation network where no previous flow records are available. Results showed that the methodology is efficient in terms of predicting the flow records and selecting the pump as turbine best efficiency point and the difference between the actual and predicted power generation was only 0.2%.

In addition, Eva Gómez-L1anos et al. [7] developed a methodology for potential hydro-power identification in water supply system and the possible turbine installation using a MATLAB routine. The results clarified the interaction between the design flow, maximum head and amount of generated power. Moreover, the study quantified the amount of potential hydro-power in 200 mm water pipes diameter, reaching up to 87 kW based on a flow rate ranging from 0.01 m^3/s to 1 m^3/s and total head ranging from 10 m to 120 m.

Asmae Berrada et al. [8] assessed the efficiency of installing micro hydropower in water networks in morocco. By the use of optimization algorithm, the hydropower plants were sized and both financial and environmental impacts were studied. The results showed that the micro hydropower plants will eliminate a yearly average of 282t of carbon dioxide with an output power of 69 kW. Furthermore, the financial analysis showed a gain ranging from 900,000 euros to 1,800,000 euros.

The optimization of water supply networks by relying on energy recovery method using pump as turbines was also studied by Gustavo Meirelles Lima et al. [9]. The results showed that increasing costs by increasing pipe diameters can be neglected due to energy recovery profit. Moreover, in low water demand fluctuation, pump as turbines can operate around its best efficiency point which makes it feasible in such network conditions.

Moreover, Abdollah Eskandari Sani [10] had numerically and analytically designed a Pelton turbine impeller. The Pelton turbine was added on the shaft of a high-pressure pump having head of 54 bars and flow of 320 m^3/h and supplying the reverse osmosis membranes of the desalination plant with sea water. The rejected water pipe from the reverse osmosis filters suppled the Pelton turbine with water at head of 52 bars and flow rate of 195 m^3/h in order to recover part of the input power. The on-site performance tests showed a decrease of 26% in the input power as a result of installing the Pelton turbine.

As part of the continuous research in the field of hydropower generation, Min Liu et al. [11] developed a theoretical model for pump as turbines energy performance. The model eased the path for determining the best efficiency point for the pump under turbine mode. The study concluded that the best efficiency point for the pump at turbine mode is slightly lower than when it's on pump mode. Moreover, pump as turbines proved to be effective for power generation under high flow rate circumstances.

Kenneth E. Okedu et al. [12] studied the possibility of exploiting small hydropower in Cross River State in the southern part of Nigeria. Active streams and rivers across the area were investigated and since those areas were mountainous and not connected to the power grid, the small hydropower plants were considered as a viable solution for power production to serve the population. Even though this technology resembled a sustainable source for electricity, the challenge was in the fluctuation in streams and rivers water flow from season to another.

The performance of mini hydro turbines in Bumaji stream in Nigeria was examined by Roland Uhunmwangho et al. [13]. The examination was done in rainy seasons of the year where the flow rate in the river was at its maximum. The result of examining and comparing the mini hydro turbines was as follows. The Crossflow turbines were the cheapest in generating power with value of 100.8$/MWh and a payback period of less than 5 years in addition to a yearly saving of 63,000$. On the other hand, the Kaplan turbines saved up to 52,000$/year and 106.2$/MWh power cost with a 5 years payback period.

Ismail Adal Guiamel & Han Soo Lee [14] identified the possible hydropower locations and their potential capacities based on the modeling of Mindanao River Basin in Philippine. Based on the river discharges, the model located 33 potential sub-basins which can produce a monthly average power of 5,551.35 MW. Furthermore, the study assured the effect of flow fluctuation from season to another on the potential power to be produced by the installed hydropower plants.

Arihan Sonawat et al. [15] designed a multi-purpose positive displacement hydro turbine to displace the pressure differential control valve found on the hot water transmission pipelines and supply 1.41 million household in Republic of Korea. The designed turbine succeeded in maintaining the required hot water flow and pressure to be supplied to end users. Moreover, the turbine succeeded to generate 15,768 kW h per year in case all pressure deferential control valves within the hot water supply grid were replaced. The installed turbines reduced the heating losses in the system and were able to save 2.64 million $ of fuel cost which was estimated by 0.88 billion $. Nevertheless, the generated power from the turbines reduced the CO_2 emissions by 6.7t.

To assure the choice of adopting hydropower plants as a sustainable source of energy from financial point of view, Sebastijan Seme et al. [16] conducted a multi criteria evaluation for the optimal electricity price produced by solar power plants and small hydropower plants. The viability of investing in solar or small hydropower plants was tested on different electricity purchase prices. The investment was categorized as viable in case it achieved a 10-year payback period based on 41.94 €/kWh electricity price in Slovenia. The study concluded that in order to achieve a 10-year payback period by installing solar or hydropower plants, it will be required to increase the reference price of electricity by 3.3 times in case solar power plants were installed. However, it will be increased by 1.4 times only in case small hydropower plants were adopted.

The mentioned studies have proven the possibility of producing a legitimate amount of power by installing different types of turbines at excess pressure points in irrigation, water supply networks, wastewater treatment plants discharge points and desalination plants and other systems such as in cooling water system [17]. The studies also discussed the feasibility of installing specific kinds of turbines in supply networks due to flow and pressure variation because of demand fluctuation along the year, which affected the installed turbine power efficiency. Moreover, researches were considering either the availability of high flow & low pressure to assess the functionality of installing hydro turbines such as in water networks, irrigation networks and water streams, or the availability of low flow & high pressure such as in desalination plants. On the other hand, none of the studies covered the potential embedded power in main water transmission pipes, where high steady flow and fixed high pressure are available., which will be covered in this paper.

In this research, the potential hydro-power in an existing pressurized transmission water pipe where high flow rate and high-pressure values are available was quantified based on the original design. Multiple proposed velocity scenarios were conducted to reach the optimized solution and to make sure no excess pressures are available due to the over design of the existing system. Moreover, an economical evaluation was conducted for installing hydro-turbines to produce energy. The feasibility of the proposed solution to benefit from the available residual pressure was based on the energy payback period after optimizing the design of water transmission system. The existing pressure reducing valve at each takeoff point was considered as a hotspot, where the proposed hydro-turbines shall be installed to induce the residual pressure available and recover energy, in addition to reducing CO_2 emissions resulting from electricity production.

2. Case study

The paper covers a case study of an existing water transmission pipeline located in the west of Saudi Arabia. The existing pipeline conveys potable water from a main water reservoir located at level 1,790 m to different water tanks referred to as takeoff points. The main water transmission pipe is made of carbon steel grade (X65) with diameter of 40" and total length around 230 km.

It was necessary to install a main pump station (PS1) at the beginning of the transmission system to convey the required flow to from takeoff point 1 until Takeoff point 6. However due to the existing topography where takeoff points 7 & 8 are located at higher ground levels 2,230 m & 2400 m respectively, an intermediate boosting pump station (PS2) was required after 165 km from the start of the main transmission line. Below Fig. 1 shows the overall layout of the water transmission system, and Fig. 2 shows the ground level profile.

Each takeoff point is 500 m far from the connection with the main pipe line and it consists of pressure reducing valve (PRV), flow control valve (FCV) and a water tank as schematized in Fig. 3 below.

Moreover, the below Tables 1 and 2 include the existing data about the existing flow rate to each takeoff point and the capacities of the existing pump stations. The water transmission system was simulated on WaterCAD software conveying the design flow to each takeoff point by entering the actual ground elevations, pipes diameters, control valves and pump stations capacities as provided in the original design. The simulation is illustrated in the hydraulic grade line of the transmission pipeline shown in Fig. 4. According to the hydraulic grade line, it is possible to identify the residual pressures at each takeoff point, which range from 698 m at takeoff point 1–106 m at takeoff point 8.

3. Methodology

After simulating the existing conditions of the water transmission pipeline on WaterCAD, and based on the hydraulic analysis of the executed pipeline on ground; work will be done to quantify the embedded power, optimize the design of the transmission line, and evaluate the proposed solution financially and environmentally. Fig. 5 illustrates the study methodology in a schematic presentation. The first phase is to identify the hotspots where there are residual pressures within the system. At the identified hotspots, the potential amount of power to be harvested if hydro-turbines are added will be calculated.

In the second phase, the transmission water system is simulated and redesigned using MATLAB routine by changing the maximum allowed velocity (V) in the water transmission pipeline. Four velocity scenarios are adopted and are as follow:

- Scenario 1: $V \leq 1$ m/s
- Scenario 2: 1 m/s $\leq V <$ 1.5 m/s
- Scenario 3: 1.5 m/s $\leq V \leq$ 2 m/s
- Scenario 4: 2 m/s $\leq V \leq$ 2.5 m/s, this scenario maintains the velocities as per the original design; however, it is raised within the scenario range from takeoff 4 until takeoff 8.

According to the different applied scenarios, the pump stations head and pipe diameters will be modified to allow conveying the required design flow rate to each takeoff point, leading eventually to adaptations in the residual pressure amount at each hotspot due to the change in the system's pressure and major losses.

In the third phase, a MATLAB coded program is conducted to enable the selection of the best fitting hydro-turbine type at each of the identified hotspots, in addition to quantifying the amount of power produced after installing the turbines. Nevertheless, it will be able to estimate the electro-mechanical cost for each of the installed turbines based on the amount of power produced and available residual pressure. This program will undergo the scenarios described in phase 2, allowing for system comparisons based on the amount of hydro-power generation and electro-mechanical cost.

The fourth phase is for the financial and environmental evaluation of the simulated scenarios with respect to the original design. Starting with the financial evaluation, the electro-mechanical cost of each hydro-power plant will allow forecasting its total cost. Moreover, the power produced by every hydro-power plant allows for electricity saving cost by investing the produced power in supplying the main pump stations or supplying the surrounding facilities around the hydro-power plants. Accordingly, the energy payback period for each of the studied scenarios can be calculated. Concerning the environmental evaluation, the system's self-production of power through the proposed hydro-power plants, will allow for carbon footprint minimization due to the reduction of fuel combustion required for supplying the pump stations and the surrounding facilities with electricity.

3.1. Hotspots identification

The WaterCAD simulation allowed the identification of the location of the available residual pressure and thus pointing out each hotspot location. The residual pressure was dissipated using a pressure reducing valve (PRV) prior discharging into the designated water tank at all of the existing takeoff points. The embedded power at each hotspot was quantified by following equation (1) described by Eva Gómez-Llanos et al. [7] and Sanjoy Roy [18]:

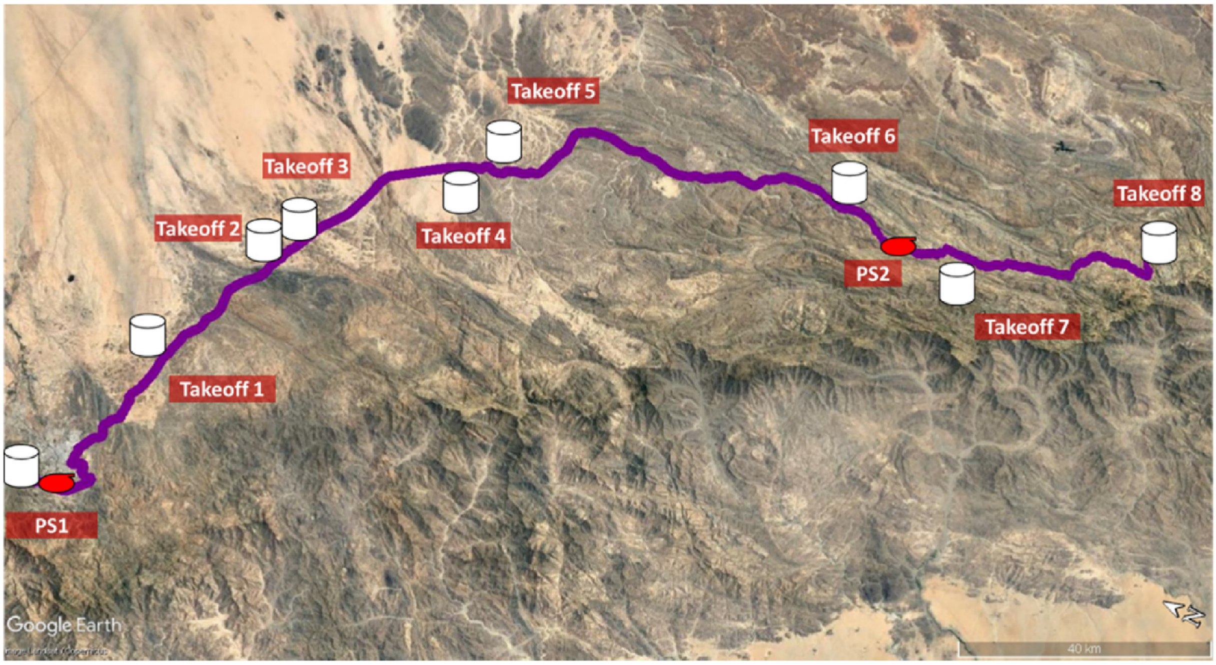

Fig. 1. Overall plan layout for water transmission system.

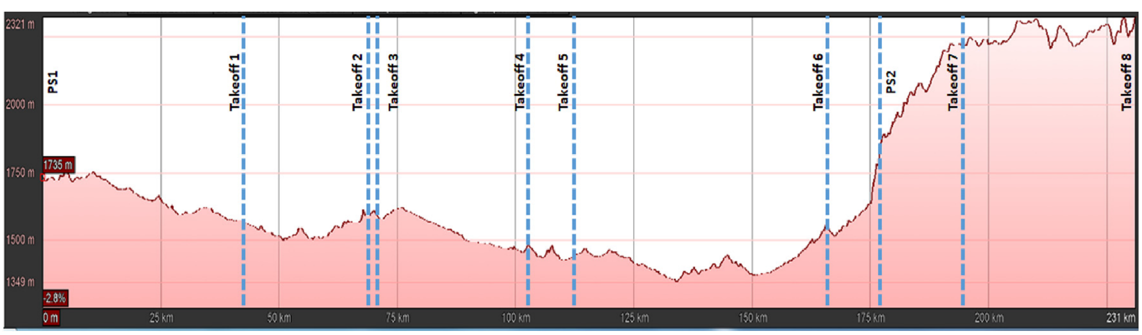

Fig. 2. Ground level profile.

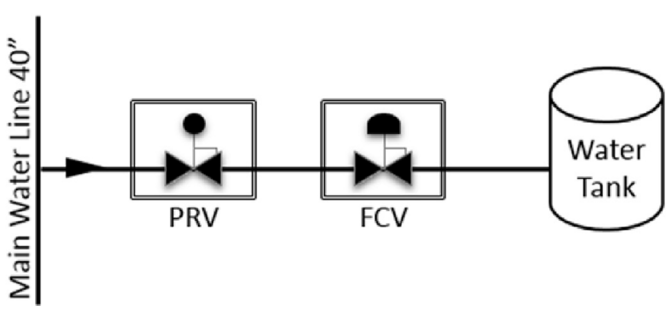

Fig. 3. Typical takeoff point components.

$$p = \eta g \rho Q H_{net} \quad (1)$$

Where:

P = Power Generated by Turbines (kW).
η = Turbine Generating Efficiency (%)
g = Gravity acceleration constant (approximately 9.8 m/s^2).
ρ = Water density (1000 kg/m^3).
Q = Water flow (m^3/s).
H_{net} = Net head (m) (Total head − Friction Loss).

Table 1
Original design - branches diameters & flow rates.

Location	Branches Diameter (inch)	Flow (L/s)
Takeoff 1	12	176
Takeoff 2	6	12
Takeoff 3	6	18
Takeoff 4	12	119
Takeoff 5	20	347
Takeoff 6	24	463
Takeoff 7	12	116
Takeoff 8	40	579
	Total	**1,829**

Table 2
Original design - pump stations capacities.

Tank	Head (m)	Design Flow (m^3/d)
PS1	610	158,058
PS2	530	60,000

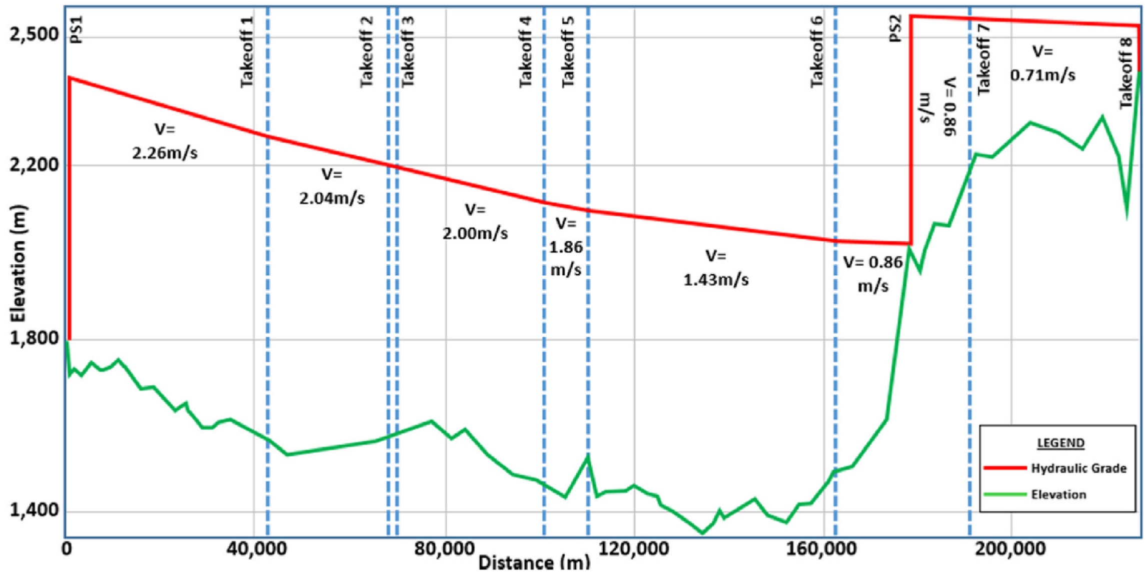

Fig. 4. Main pipe line (40″) hydraulic grade line.

Hydro-power turbines efficiency varies based on the design and actual capacity of the introduced turbine as reflected in the below curves in Fig. 6 shared by İ.Ethem Karadirek et al. [19]. In this study, the turbine operating efficiency was considered 80% where it usually falls between 80% and 90% in typical hydro systems [20].

Table 3 summarizes the enumerated embedded power resulting from the residual pressure in each of the PRVs and the amount of flow passing through.

3.2. Simulating velocity scenarios

3.2.1. MATLAB model

The model was done in order to facilitate the designing process of the water transmission line. In the model, the systems constraints such as pipes lengths and elevations were identified and accordingly the pump stations head and pipe diameters were adjusted as the allowed velocity changed from 1 to 2.5 m/s consecutively. The adjustments were done in order to assure zero residual pressure at the downstream of each part of the system which are defined as follows:

- Part 1 starts from main pump station number one (PS1) until takeoff point 6.
- Part 2 starts from boosting pump station number two (PS2) until takeoff point 8.

The friction losses in each part of the system were calculated by applying Hazen-Williams equation (2) [21]:

$$h_f(\mathrm{m}) = 10.67\ L\ \left(\frac{AxV}{C}\right)^{1.852}\ D^{-4.87} \tag{2}$$

Where L is the main pipe segment length (m), A is the cross sectional area of the pipe line (m^2) and equals to($\frac{\pi d^2}{4}$), D is the pipe diameter (m), C is Hazen Williams Coefficient (dimensionless) and assumed as 140 (1) for Carbon Steel Pipes and V is the Velocity (m/s).

Because the elevations of the start and end of each part of the system were known, the static head could be calculated. This determined the pumps head after adding the losses due to friction along the transmission pipelines based on the below equation (3) [21].

$$H_p = Z_d - Z_p + \sum_0^n h_f \tag{3}$$

Hp is the calculated pump head (m), Zd is the elevation of the system downstream (m) which is PS2 in part number 1 and takeoff point 8 in part number 2, Zp is the elevation of the pump under design (m) and $\sum_0^n h_f$ is the summation of the friction losses along the main pipe segments (m).

As we run the MATLAB model by changing the velocity from less than 1 m/s to maximum of 2.5 m/s, the program calculated the required pump station capacity based on the available friction losses and static head, in addition to the pipe diameters required to attain the simulated scenario velocity and ending up with quantifying the residual pressures at each takeoff point.

3.2.2. MATLAB model results

Table 4 summarizes the amount of flow and the proposed diameters (Ø) of the whole system starting from PS1 until Takeoff 8.

The below Table 5 shows the new proposed pump stations head for each of the scenarios.

Fig. 7 reflects the change in the hydraulic grade line of the main water pipeline as the pipe sizes and pumps heads have changed due to the change in the maximum allowed velocity from the original design.

Applying new pump heads and changing the pipe diameters, reflected on the amount of residual pressure to be dissipated by each of the PRVs located at the takeoff points. Below Table 6 summarizes the results of the simulated systems.

3.3. Turbine selection

3.3.1. Turbine type & sizing

To ease the selection process at each hotspot in each of the scenarios, the MATLAB software was developed to enable the selection of the best fitting turbine type. Having the available pressure and flow as an input at each hotspot, the software calculated the electro-mechanical cost of the selected turbines and the amount of power generated. Proposed turbine types within the software were Francis, Kaplan & Pelton that are a combination of widely used impulse and reaction turbines. Fig. 8 illustrates turbine

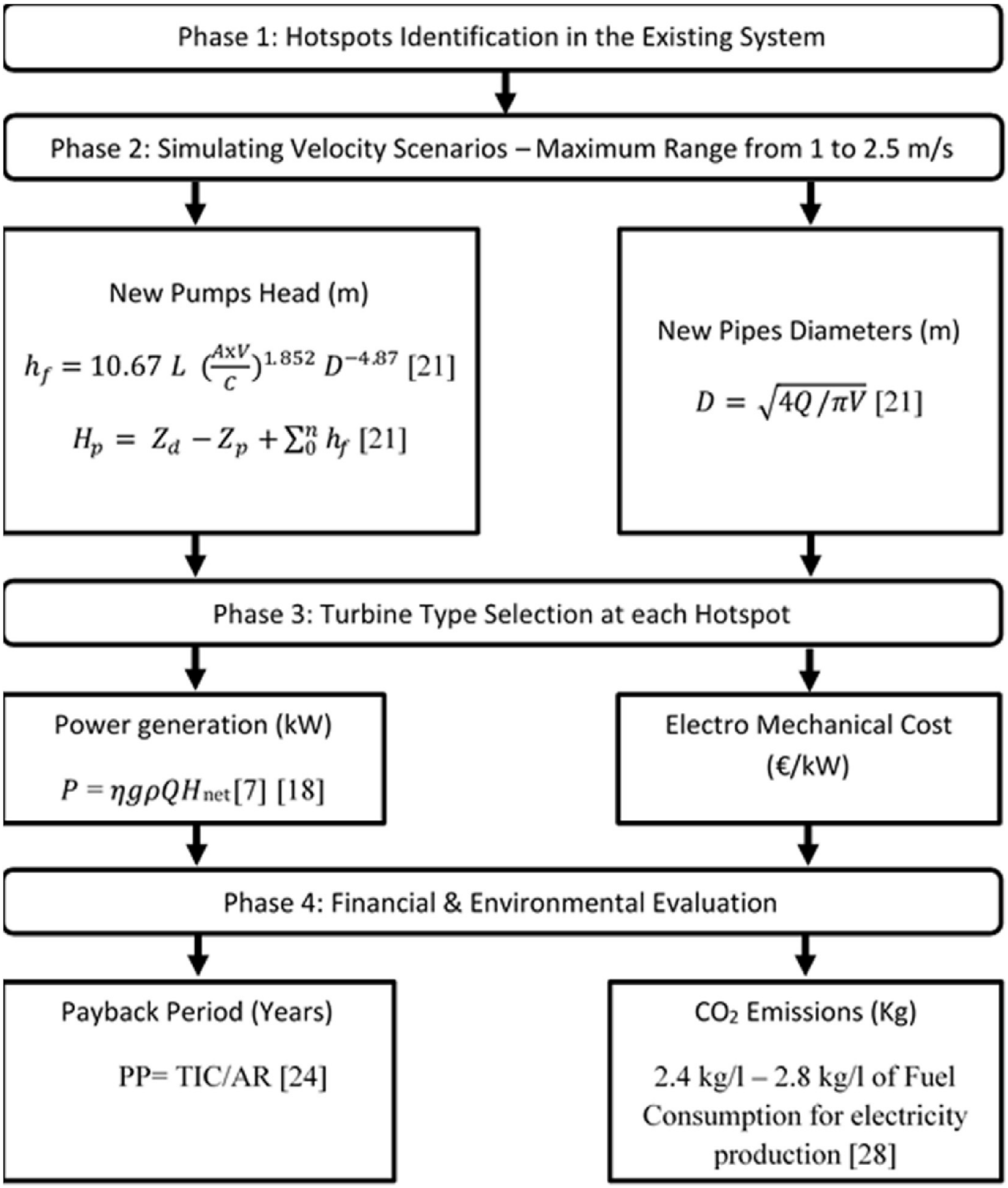

Fig. 5. Methodology schematic presentation.

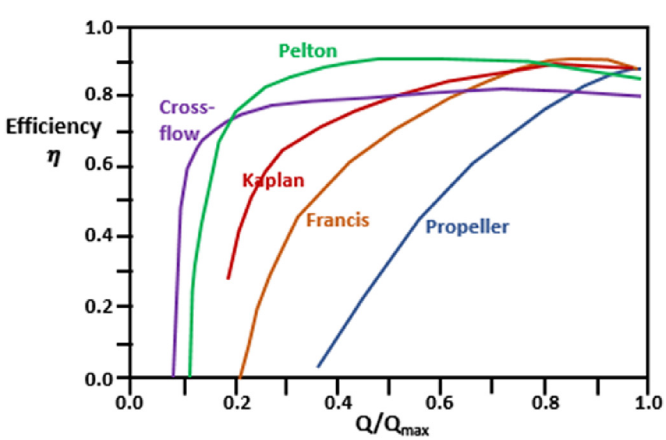

Fig. 6. Turbines Efficiency Curves by İ.Ethem Karadirek et al. [19].

Table 3
Original design - embeded power estimation.

Hotspot Location	Residual Pressure - H_{net} (m)	Flow (m^3/s)	Power (kW)
Takeoff 1	698.28	0.176	965
Takeoff 2	594.44	0.012	54
Takeoff 3	545.28	0.018	76
Takeoff 4	604.64	0.119	567
Takeoff 5	552.52	0.347	1,506
Takeoff 6	514.27	0.463	1,869
Takeoff 7	294.47	0.116	267
Takeoff 8	105.87	0.579	481
Total		**1.829**	**5,784**

Table 4
Pipe Diameters for Maximum Allowed Velocities from 1m/s to 2.5m/s

Location	PS1						PS2	
	Take off 1	Take off 2	Take off 3	Take off 4	Take off 5	Take off 6	Take off 7	Take off 8
Flow (m^3/s)	1.829	1.653	1.641	1.623	1.504	1.157	0.694	0.579
				Scenario 1				
Ø (inch)	64	60			56		40	36
V (m/s)	0.88	0.91	0.90	0.89	0.95	0.73	0.86	0.88
				Scenario 2				
Ø (inch)	56	48				40	32	28
V (m/s)	1.15	1.42	1.41	1.40	1.30	1.43	1.34	1.46
				Scenario 3				
Ø (inch)	44	42		40		36	28	26
V (m/s)	1.86	1.85	1.84	2.00	1.86	1.76	1.75	1.70
				Scenario 4				
Ø (inch)	40				36	32	24	22
V (m/s)	2.26	2.04	2.03	2.00	2.29	2.23	2.38	2.26

Table 5
Pump stations capacities for maximum allowed velocities from 1 m/s to 2.5 m/s.

	Scenario 1	
PS1	$Q = 1.829\ m^3/s$	$H = 280\ m$
PS2	$Q = 0.694\ m^3/s$	$H = 438\ m$
	Scenario 2	
PS1	$Q = 1.829\ m^3/s$	$H = 420\ m$
PS2	$Q = 0.694\ m^3/s$	$H = 497\ m$
	Scenario 3	
PS1	$Q = 1.829\ m^3/s$	$H = 650\ m$
PS2	$Q = 0.694\ m^3/s$	$H = 535\ m$
	Scenario 4	
PS1	$Q = 1.829\ m^3/s$	$H = 856\ m$
PS2	$Q = 0.694\ m^3/s$	$H = 740\ m$

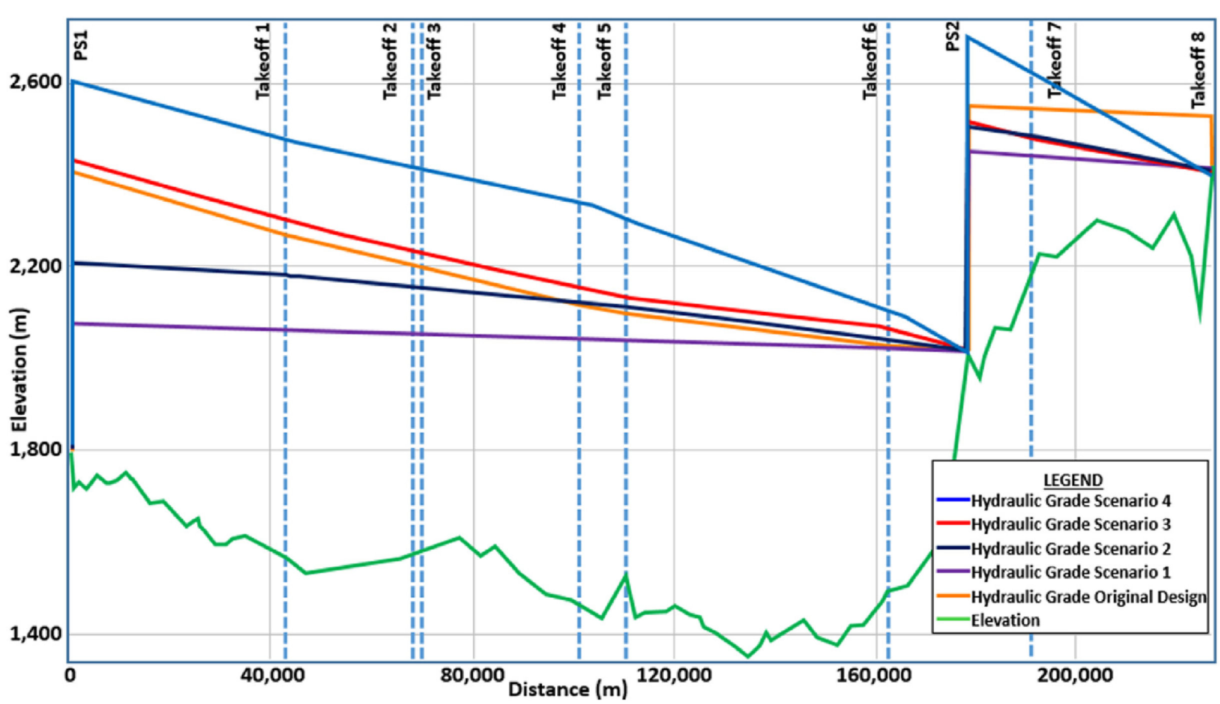

Fig. 7. Hydraulic Grade Line Variation for studied scenarios.

Table 6
Pump stations capacities for maximum allowed velocities from 1 m/s to 2.5 m/s.

Location	Residual Pressure (m) Scenario 1	Residual Pressure (m) Scenario 2	Residual Pressure (m) Scenario 3	Residual Pressure (m) Scenario 4
Takeoff 1	487.5	611.1	778.6	930.9
Takeoff 2	432.1	540.4	674.9	814.5
Takeoff 3	431.6	539.0	682.4	821.3
Takeoff 4	526.7	612.1	695.7	834.6
Takeoff 5	484.5	564.1	644.6	766.7
Takeoff 6	503.2	526.1	559.6	589.5
Takeoff 7	198.7	248.9	276.4	409.1
Takeoff 8	0.00	0.00	0.00	0.00

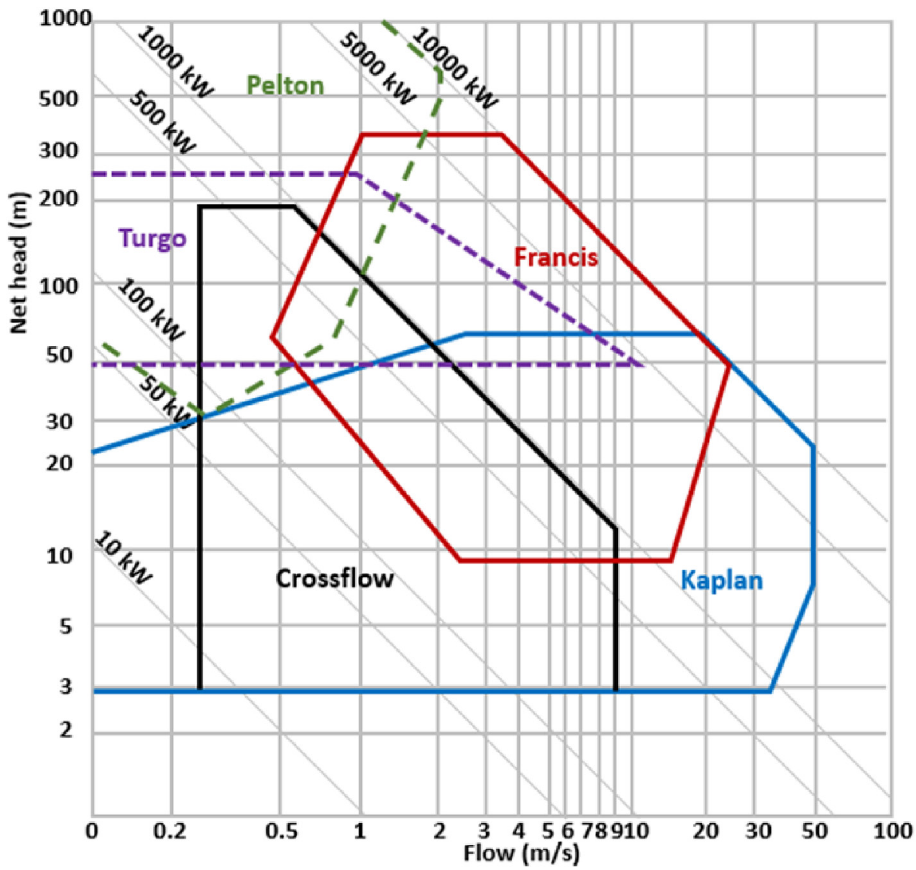

Fig. 8. Turbine selection chart by penche & minas [22].

selection chart on which the MATLAB software was built on by Penche & Minas [22].

3.3.2. Turbine electro-mechanical cost

Electro-mechanical cost is considered as a major aspect in determining the hydro-power plant budget for any project. Electromechanical equipment that includes turbine & alternator resembles 65% of the total plant cost [5]. The below formulated equations in Table 7 are for Francis, Pelton & Kaplan turbines shared by Ogayar & Vidal [23] can calculate the electro-mechanical cost (€/kW) as a function of power (kW) & head (meter).

Table 7
Turbines electo-mechanical cost by ogayar & vidal [23].

Turbine Type	Electro-Mechanical Cost (€/kW)
Pelton	17,693 $P^{-0.3644725}$ $H^{-0.281735}$
Francis	25,698 $P^{-0.560135}$ $H^{-0.127243}$
Kaplan	33,236 $P^{-0.58338}$ $H^{-0.113901}$

3.3.3. Turbine selection results

The suitable turbine type for each hotspot was selected after running the software in each scenario. Based on the available residual pressure and flow rate, power was generated and accordingly the electro-mechanical cost was determined. Tables 8 and 9, reflect the results outputted from the software based on the allowed velocities. Takeoff points 2 & 3 were considered out of range since the design flow rate was less 0.02 m^3/s and accordingly the potential embedded power at the takeoff points was negligible. As for takeoff 8, the residual pressure was null as per the designed system in each of the studied scenarios.

3.4. Financial & environmental evaluation

3.4.1. Financial evaluation

3.4.1.1. System cost optimization. After modifying the allowed velocity of the executed system, the resulted changes in pump stations capacities, pipe sizes and the introduced hydro-power plants

Table 8
Turbine Selection Results for maximum allowed velocities 1 m/s & 1.5 m/s.

Take off	Scenario 1			Scenario 2		
	Turbine Type	Generated Power (kW)	Electro-Mechanical Cost (€/kW)	Turbine Type	Generated Power (kW)	Electro-Mechanical Cost (€/kW)
1	Pelton	671.45	288.49	Pelton	841.69	249.30
2	Out of Range	–	–	Out of Range	–	–
3	Out of Range	–	–	Out of Range	–	–
4	Pelton	492.34	316.07	Pelton	572.17	286.82
5	Pelton	1,316.30	226.12	Pelton	1,532.56	204.95
6	Pelton	1,822.81	198.69	Pelton	1,905.76	193.06
7	Pelton	179.94	600.32	Pelton	225.41	519.00
8	–	–	–	–	–	–

in the analyzed scenarios, affected directly on the total system cost. It was noticeable that allowing lower velocities increases the total system cost because of the need of larger pipe diameters, which cover 77%–95% of the total cost in the scenarios under study. Table 10 found below compares the total system cost after allowing velocities from 1 m/s to 2.5 m/s with respect to the existing situation after installing Pelton turbines at each takeoff point except takeoff points 2 & 3 which were considered out of range since the design flow rate was less 0.02 m^3/s.

3.4.1.2. Energy payback period. The viability of introducing the turbine technology to water transmission pipelines in order to harvest power can be determined based on the energy payback period of installing the required hydro-power plant. The payback period (PP) which is expressed in years (y) can be calculated as per equation (4), and it is the proportion of total installation cost (TIC) to the annual revenue (AR) [24].

$$PP = TIC/AR \tag{4}$$

The total installation cost covers the civil works cost, electro-mechanical cost of the hydro-power plant and the yearly operation and maintenance (O&M). O&M cost varies from 4% to 6% based on the size of the hydro-power plant as described by IRENA [25]. Based on the proposed hydropower plants capacities, the O&M cost was assumed to be 4%.

The execution and operation of the pump stations is considered as part of the total installation cost, since it is the part that consumes energy and accordingly it's a main aspect for calculating the energy payback period. Moreover, the pumping stations operational cost was assumed to be 3% of its execution.

The annual revenues are determined from the annual savings of supplying electricity generated from the hydro-power plant to the existing governmental facilities such as pump stations, guardhouses and control buildings. Since the system is located in the Kingdom of Saudi Arabia, the power cost for governmental asset is 0.077 €/kW [26]. Table 11 reflects the energy payback period of the simulated systems based on the different allowed velocities.

3.4.2. Environmental evaluation

Power plants exhausts and power generators release CO_2 due to fuel combustion in order to produce power. Adopting the turbine technology to harvest power will have direct impact on the usual carbon footprint size. To estimate the amount of CO_2 emission reduction, the amount of diesel fuel required by regular generators to produce the same amount of power from the installed hydro-power plants have to be determined. The fuel consumed by the diesel generator depends on two aspects; the characteristics of the generator and the type of fuel. Since The existing pump stations are supplied by electricity through on-site generators, the study had quantified the total amount of power needed to supply the existing pump stations in addition to the power produced by the turbines in the adopted scenarios. Based on the calculated power consumed by the pump stations and supplied by the turbines, the volume of diesel required for power production was calculated using the online calculator shared by GlobalPwr [27].

Based on E. Alsema [28], the quantity of CO_2 emissions usually falls in the range of 2.4–2.8 kg/l of diesel consumption. By adopting 2.6 kg/l of diesel consumption for power production, the reduction in CO_2 emissions by relying on the power produced from the hydro-power plants was determined.

Regarding the existing water transmission system conditions, the amount of power required to supply the executed pump stations by the on-site generators is 25,127 kW h. And the total amount of emitted carbon dioxide is quantified by 165,783t per year.

Table 12 reflects the amount of fuel required for power generation along the year to produce the same amount of power produced by the hydro-turbines in each of the scenarios in addition to the amount of CO_2 emitted which can be deducted by adopting hydro-turbines technology.

Table 9
Turbine Selection Results for maximum allowed velocities 2 m/s & 2.5 m/s.

Take off	Scenario 3			Scenario 4		
	Turbine Type	Generated Power (kW)	Electro-Mechanical Cost (€/kW)	Turbine Type	Generated Power (kW)	Electro-Mechanical Cost (€/kW)
1	Pelton	1,072.40	213.17	Pelton	1,282.17	189.93
2	Out of Range	–	–	Out of Range	–	–
3	Out of Range	–	–	Out of Range	–	–
4	Pelton	650.32	264.05	Pelton	780.16	234.75
5	Pelton	1,751.27	188.02	Pelton	2,082.99	168.09
6	Pelton	2,027.11	185.51	Pelton	2,135.42	179.37
7	Pelton	250.31	485.02	Pelton	370.48	376.45
8	–	–	–	–	–	–

Table 10
Cost variation in each scenario.

Scenario	Pump Stations Construction Cost (€)	Hydro-Power Plants Cost (€)	Piping & Accessories Cost (€)	Total Cost (€)
Original Design	32,053,845	2,196,102	219,685,800	253,935,747
Scenario 1	17,634,060	1,718,718	381,045,500	400,398,278
Scenario 2	24,051,090	1,804,540	282,176,300	308,031,930
Scenario 3	33,709,425	1,887,775	211,373,600	246,970,800
Scenario 4	63,065,142	1,998,906	186,086,200	251,150,248

4. Results & discussion

Adjusting the maximum allowed velocity in the transmission pipeline from the original design changed the pipe diameters of the transmission pipeline which in turn affected the pump stations head.

Table 13 reflects the change in pump stations head & cost for each of the scenarios.

The changes in pipe diameters and pump heads had an effect on the construction cost of the transmission system. In addition, the change in the hydraulic grade line reflected on the amount of residual pressure dissipated in the pressure reducing valves at each of the takeoff points in each of the studied scenarios. Additionally, the amount of power generated by the hydro-power plants, the energy payback period, and the amount of reduction in the carbon footprint varied from one scenario to another. Below Fig. 9, reflects the percentages of construction cost, residual pressure, generated power, energy payback period and reduction in carbon footprint

Table 11
Energy Payback Period Estimation

Pump Stations PS1 & PS2 Cost (€)	Pump Stations O&M Cost (€/year)	Hydro-Power Plants Cost (€)	Hydro-power Plants O&M Cost 4% (€/y)	TIC (€)	AR (€/y)	PP (y)
			Original Design			
32,053,845	961,615	2,196,102	87,844	35,299,406	3,814,411	9.25
			Scenario 1			
17,634,060	529,022	1,718,718	68,749	19,950,549	2,902,396	6.87
			Scenario 2			
24,051,090	721,533	1,804,540	72,182	26,649,344	3,424,938	7.78
			Scenario 3			
33,709,425	1,011,283	1,887,775	75,511	36,683,994	3,879,437	9.46
			Scenario 4			
63,065,142	1,891,954	1,998,906	79,956	67,035,959	4,486,382	14.94

Table 12
Required Fuel Amounts for Estimated Power Production & CO_2 Emissions.

Power Produced/year (kW)	Yearly Diesel Amount (L)	Yearly CO_2 Emissions (t)
	Original Design	
49,537,800	13,347,361	38,254
	Scenario 1	
39,269,770	10,580,765	30,325
	Scenario 2	
44,479,718	11,984,523	34,348
	Scenario 3	
50,382,305	13,574,903	35,295
	Scenario 4	
58,264,707	15,698,721	40,817

Table 13
Pump Stations Head & Cost Variation.

Pump Station	Head (m) Original Design	Head (m) Scenario 1	Head (m) Scenario 2	Head (m) Scenario 3	Head (m) Scenario 4
PS1 (Q = 1.829 m^3/s)	610	280	420	650	856
PS2 (Q = 0.694 m^3/s)	530	438	497	535	740
Total Execution Cost Including one year O&M (million €)	33.02	18.16	24.77	34.72	64.96

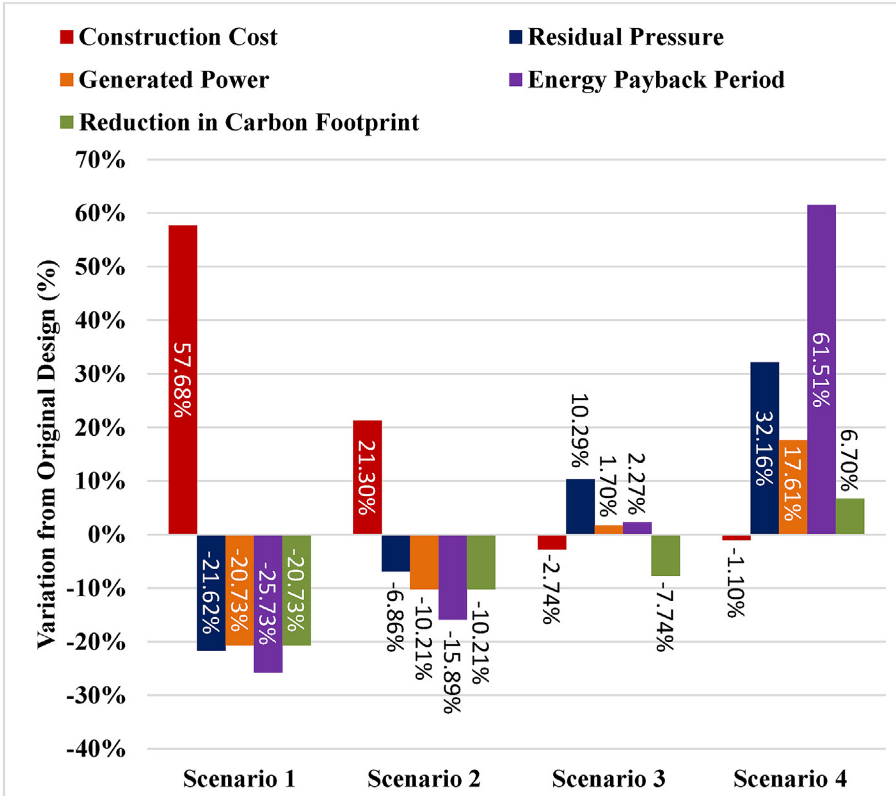

Fig. 9. *Percentage of Variation from Original Design.*

variations in each of the studied scenarios from the original design in case hydro-turbines where introduced to it.

It's recommended to adopt a hybrid system that optimizes the design of the transmission water line and reduces the system's cost, while preserving an energy payback period for installing hydro-turbines for not more than 10 years.

Based on the adopted case study and as illustrated in Fig. 10, it is recommended to adjust the velocity to range between 1.5 & 2 m/s as reflected in scenario 3, where the variations in pipeline execution cost and total energy cost from the original design have intersected. Moreover, installing hydro turbines is still considered viable since the energy payback period is around 10 years.

As for the reduction in carbon footprint, the results showed that supplying part of the pump stations required electricity by the hydropower produced by the hydro turbines will reduce the amount of CO_2 emitted. Below Fig. 11 shows the amount of emitted CO_2 in case no hydro turbines were installed versus the case if

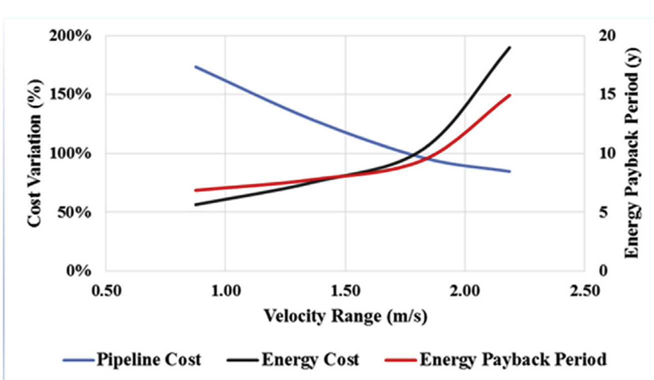

Fig. 10. *Energy Payback Period & Cost variation from Original Design.*

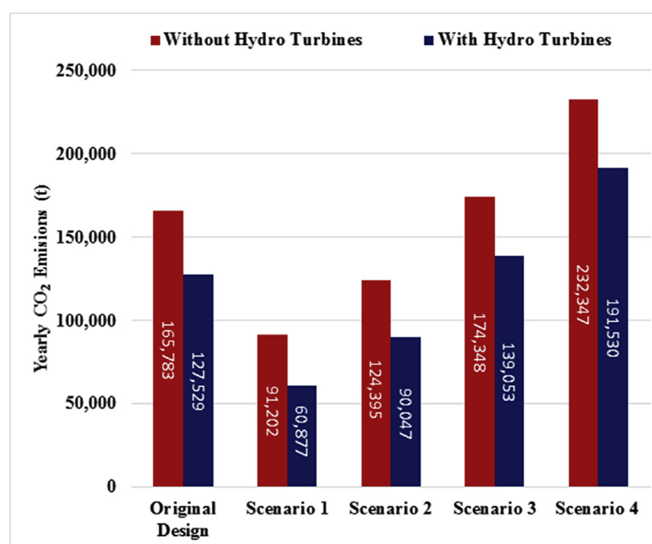

Fig. 11. Yearly CO_2 emissions comparison (with & without hydro turbines).

- The total installation cost of hydro-power plants and pump stations increased by 336% when the allowed velocity increased from 1 m/s to 2.5 m/s however; the annual revenue had increased by 155% only. This un-proportional increase between the total installation cost and the annual revenue resulted in having less energy payback period by 46%.
- A major reduction in CO_2 emissions was triggered and estimated by 17%–33% in case hydro turbines were installed. This reduction is due to reducing diesel combustion to supply the pumping stations with electricity.

hydro turbines were added.

In addition to what was indicated through the results, the following points were demonstrated:

5. Conclusion

The paper discussed the theoretical application for recovering energy by adding hydro-turbines at potential hotspots where residual pressures are available. Based on the simulated scenarios, the results confirmed the following:

- Allowing higher velocities in the transmission system will increase the amount of residual pressure and consequently the power generation amount.
- System's cost reduced as the allowed velocity increased to a limit where it started to increase due to pump stations cost, which increased massively due to the larger heads required to convey the needed flow rate.

Regarding turbines capability to produce a legitimate amount of power when installed in water transmission pipe lines where high flow and pressures are available, the paper proved the ability to have hydropower plants with a capacity ranging from 650 kW up to 2 MW based on the adopted scenario. However installed hydropower capacities in other systems were as follows:

- Ranged from 3 kW up to 234 kW when installed at the discharge points of the wastewater treatment plants as evidenced by Christine Power et al. [4].
- 196 kW when installed to recover the kinetic energy in the rejected water pipe from the desalination plant filters [10].

From an economic perspective, installing traditional turbines in major water transmission systems seemed to be feasible in contrary to what was proven by J. García Morillo et al. [5] for installing traditional turbines in irrigation networks since the payback period was less than 10 years in all of the scenarios except scenario number 4. The reason behind the viability of installing traditional turbines in water transmission pipelines is that transmission lines are designed on a steady flow, opposite to irrigation systems which have a fluctuating flow along the year due to climate and demand changes which affect turbines efficiency.

Finally, this work was done to become a roadmap for future in depth researches that would cover the technicality of installing hydro turbines in similar systems. Moreover, the paper had theoretically proved the possibility of producing legitimate amount of power in water transmission pipe lines where there is a case of stead high flow and high pressure, in addition to the financial and environmental impacts.

Credit author statement

Youssef Itani: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Writing - review & editing. Mohamed Reda Soliman: Supervision, Writing - review & editing. Maher Kahil: Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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