Energy Optimization and Cost Reduction in Water Distribution Networks

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***Abstract*—Since the majority of energy consumed by water supply systems is used in transporting and distributing water, in addition to the energy required to pump the water from its sources, energy consumption is significantly associated with the water demand. Several studies have been carried out to optimize pump operations to achieve appropriate pressure and reduce the energy associated with controlling water levels in storage facilities. In this paper, we develop an optimization and decision support technique for a Water Distribution Network (WDN) that considers energy efficiency by limiting the energy consumption of transport and distribution water operations. Therefore, three considerations are taken into account to reduce energy usage, which are: a) the tank demand pattern is redistributed using a genetic algorithm; b) the reservoir serving pattern is governed by game theory c) a decision-making algorithm is also proposed to select the best-suited controlling setting of the pump and valves based on the other two considerations.**

***Index Terms*—Water Distribution Network (WDN); Energy saving; EPanet;**

I. INTRODUCTION

Water resources are critical to human survival as well as the survival of all other lifeforms [1]. Water resources are economic assets that supply a variety of services for both consumption and production activities. Water quality has gained attention due to the possibility for a wide range of services that go beyond economics and environmental requirements [2]. On the other hand, water shortage and degradation of water quality are substantial concerns in developing countries, and the management of water resources to successfully address them is frequently contentious. Those disputes are inescapable in the absence of a market and exclusive property rights. One of the water resources management objectives is the economic objectives, including the efficiency principle, which pertains to the economical use of water resources, including water and energy consumption savings [3].

Water utilities frequently explore water-saving techniques as part of their energy-saving initiatives. Many water-saving techniques are discussed in the literature, with water demand control and water-efficient design being the most prominent. These initiatives are successful because water usage is intricately connected to electrical consumption. Previous demand management studies have produced a number of data sets on water consumption demand patterns for various water uses in order to reduce water usage. Many water-saving techniques have been applied and analyzed in the literature. In addition, the impact of various water demand patterns on water consumption and their relation with the energy consumption is being explored to minimise the water consumption [4] [5].

Water management and quality monitoring are vital issues for the entire world. Each year, cleaner water may save 1.4 million children from diarrhoea, 500,000 from malaria, 860,000 from starvation, and 280,000 from drowning, according to the World Health Organization (WHO) [6]. Furthermore, 5 million individuals can be rescued from being severely disabled by lymphatic filariasis, and another 5 million from trachoma. As a result of improved and more accessible water sources, people spend less time and effort physically getting it, allowing them to be more productive in other ways. This can also improve human safety by reducing the need to travel long or risky distances to obtain water. This will have a significant influence on people's lives. Furthermore, improved water supplies lead to lower healthcare costs since people are less likely to become ill and incur medical fees, and they are better able to remain economically engaged. This explains the movement toward developing water management systems that is capable of monitoring water quality, reducing leaks, and ensuring water transportation to isolated regions. With so much advancement in water management systems, the necessity for optimising energy and cost accordingly is growing.

The authors in [7] developed a predictive model for household water end-uses using data collected in Korea over three years. However, the measured data was not fitted to normal distribution. Therefore, they recommended the log-normal regression model and the Weibull regression model as potential solutions to the problem in order to solve the problem. The research conducted in [3] resulted in developing an approach to managing the hourly water consumption patterns through the utilization of storage facilities. The scheme aimed to reduce water consumption during times of high energy demand by distributing water consumption away from peak times and toward times of low energy prices. An investigation using numerical methods is being carried out at the Bupyeong 2 reservoir catchment in Incheon, Korea. In [8], the issue with the water distribution in the Mexican Valley was considered. In order to obtain the Nash equilibrium of the three-player game involving water users, one must first resolve a special quadratic optimization problem with linear constraints. After that, the solution to the non-symmetric Nash bargaining problem was found by optimizing the results of the non-symmetric Nash product. The numerical results demonstrate that no water distribution scheme can fulfil all of the demands placed on it by domestic users. Therefore more investment is needed for further developments. Thus, another proposed mixed Nash equilibrium control for the serving of reservoirs with an intelligence algorithm for controlling actuators for water management purposes is developed in [9].

This paper shows that energy consumption can be reduced by redistributing a tank demand pattern using genetic algorithm and optimizing the reservoir serving pattern using game theory. For simulating, illustrating, and analysing water resource management phenomena, game theory is utilised. Finally, based on the preceding two actions, a decision-making algorithm is developed to assign the best-suited controlling setting of the pumps and valves. The remainder of this paper is organized as follows. In Section II, a brief description of the water distribution network model is introduced. In Section IV, the proposed algorithms and results are discussed in detail. In section V, the work is concluded.

II. PRELIMINARY NETWORK COMPONENTS

A. *Total Energy Calculation*

During the Water Distribution Network (WDN) operation, energy is distributed among the various components, and it can be dissipated by managing Pressure Reduction Valves (PRVs) and pumps. Managing the pressure levels of WDN nodes will help in reducing the amount of energy consumed by the network. The consumed energy is given by [10]

$$E = \int_0^t P\, dt = \int_0^t \gamma H Q\, dt \tag{1}$$

where P is power (W), H is head (m), γ is specific weight (N/m^3) and Q is flow rate (m^3/s).

B. *Water Consumption*

Water supply resources can be divided into two types: direct and indirect. Direct water resources are delivered directly from a source, such as a reservoir, whereas indirect water resources are held in tanks. Therefore, the water can be consumed by both direct and indirect water sources. The total water consumption can be calculated by [3]

$$Q_{day} = \sum_{i=1}^{24} [Q_n.P_n(i) + Q_u.P_u(i)] \tag{2}$$

where Q_{day} is the total consumption of water per day, Q_n is the water consumed by direct water source per day, Q_u is water consumed by indirect water source per day, $P_n(i)$ is the pattern of water consumed by direct water source per time slot, $P_u(i)$ is the pattern of water consumed by indirect water source per time slot.

C. *Cyber-Physical Systems (CPSs)*

WDN comprises hydraulic components that connect consumers to water sources, such as pipelines, valves, and reservoirs. WDN's core infrastructure is known as Cyber-Physical Systems (CPSs), since it combines physical equipment (such as sensors, tanks, and pumps) with cyber applications (i.e., SCADA, other computing software). Supervisory Control and Data Acquisition (SCADA) control data gathered from sensors concerning physical water operations and parameters for water quality and quantity such as flow rate, minerals, leakage, chemical composition, and pollutants.

D. *WDN Hierarchy*

The basic WDN is shown in Fig. 1, which includes (water sources, tanks, actuators, Flow Control Valves (FCVs), Pressure-Reducing Valves (PRVs), pumps, pipes). The water sources can be infinite external sources called reservoirs, such as rivers and lakes, which represent the input of the water system, even though they are not affected by network events, or storage facilities, which involve tanks with limited capacity and water minimum and maximum levels. However, tanks have properties such as diameter and elevation. Actuators are assigned to WDN as a pump, a mechanical energy device that transfers water flow as total head to deliver additional energy to the water fluid process, and a valve, which can restrict pressure if a Pressure-Reducing (PR) or flow if the FCV is used. In the proposed WDN, the PRV is employed, and its state is regulated as closed if the end node's pressure is more than the start node's pressure and opened if the start node's pressure is less than the pressure setting. Each component of the water network is linked together by links, which are pipes with a diameter, length, and status (closed or open) near junctions where links are joined together. The customer's demand pattern consumes water flow, and sensors are connected to each user node to gather specific information stored and managed by SCADA as time-series data form to feed a control decision-making algorithm that monitors actuators devices such as pumps and valves.

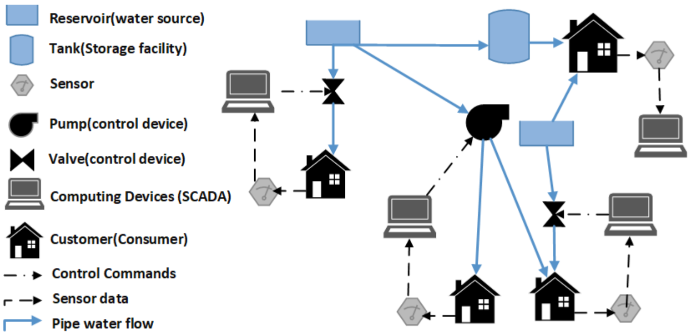

Fig. 1: WDN Hierarchy with Basic Components

III. PROPOSED ARCHITECTURE

Dataflow between EPANET and MATLAB is implemented as EPANET−MATLAB Toolkit is an open-source software that allows users to create and modify water systems, as well as use all water network components, in addition to modeling water quality and hydraulic processes such as water age, chemical concentration, pressure, and head loss [11].Using these features, the proposed architecture is demonstrated as the following :First, we design the WDN and define its component's properties for water network demands in EPANET. Second, we can generate simulation reports from EPANET or form MATLAB EPANET toolkit after defining the Simulation parameters such as time, then extract the gathered information needed as input for the algorithm. Third using integrated genetic, game theory, and decision-making algorithms to define the demand pattern of tanks, serving pattern of reservoirs, and control setting of actuators, respectively. The next section explains in detail about each of these functions.

Fig. 2: Data flow between EPANET and MATLAB

The methodology is presented as a flowchart shown in Fig. 3. First,the EPANET is used to design the desired WDN with component properties such as pipe length and diameter, Junction base demand, demand pattern, and minimum and maximum level of the tank.Second, for the 24 hours, a game theory algorithm is used (by MATLAB) to find the reservoir serving pattern by calculating the reputation, service probability, cost, utility to create the payoff matrix and find the optimal strategy of serving or declining for the three reservoirs. Also, for 24 hours, a genetic algorithm is used (by MATLAB) to find the best tank demand that minimizes the energy consumption by determining the genetic parameters then compute the selection, crossover, mutation, and elitist selection while calculating the fitness function until the maximum generation number is reached. Third, the decision-making algorithm is used (by EPANET) to select the decision of opening or to close the pump and valves according to the flow and pressure limitation for 24 hours. The three algorithms are demonstrated 1, 2, and 3.

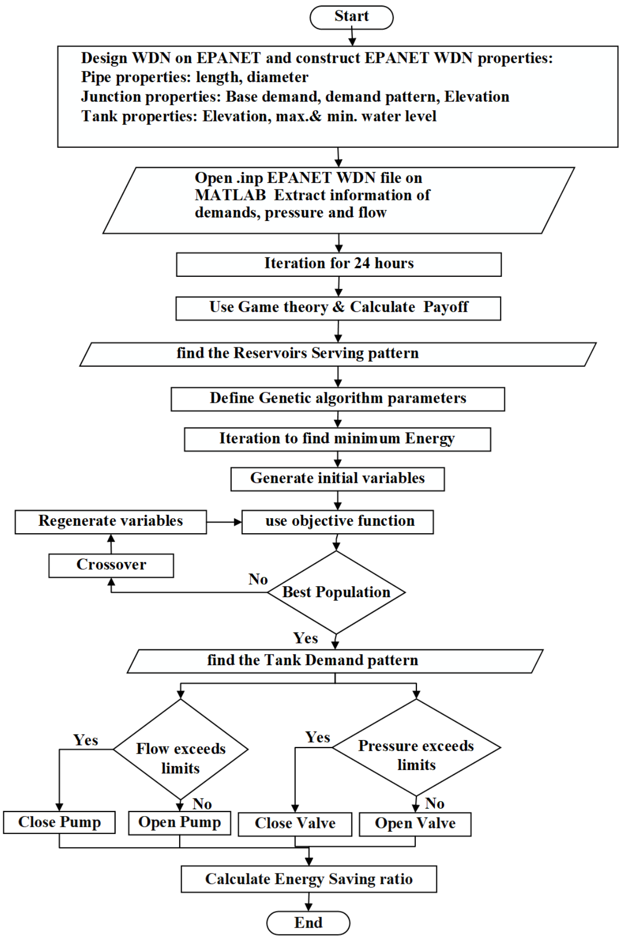

Fig. 3: Flowchart for Water Resource Management Decisions

Algorithm 1 represents the pseudo-code of the genetic algorithm to find the tank demand pattern where $N$is number of genes or the length of chromosome, M is number of chromosome, $MaxGen$ is the number of generations as a stopping criteria,Pc is a crossover ratio, Pm a mutation ratio is and Er is etilism selection ratio.

Algorithm 2 represents the pseudo-code of the game theory algorithm to find the reservoir serving pattern where R is the reputation p is the service probability, U is utility and C is the cost [9].

Algorithm 3 represents the pseudo-code of the Decision Making Algorithm for WDN to control the actuators such as pump and valves.

Algorithm 1: Genetic Algorithm for WDN

Input : $N \leftarrow 24$
$M \leftarrow 20$
$MaxGen \leftarrow 100$
$Pc \leftarrow 0.1$
$Pm \leftarrow 0.1$
$Er \leftarrow 0.05$
Output: Best Solution S

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generate random population for initialization
Calculate Fitness function
Sort Fitness Value
Selection
CrossOver
Mutation
Elitist selection
Reproduce population
find the best Chromosome S
Stop when generation = MaxGen
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Algorithm 2: Game Theory Algorithm for WDN

Input : $t \leftarrow 1$, other reservoirs decision
Output: payoff and reservoir serving pattern

- $R(t, i) \leftarrow R(t-1, i) * (1-a) + (w * a), where\ 0 \leqslant a \leqslant 1, t \geqslant 2$
- $p \leftarrow (R(t-1)*U*(1-a))/(-C+2*R(t-1)*U*(1-a)+U*a)$
- **if** *reservoir serves* **then**
- payoff$_{serve} \leftarrow p * (-C + R(t) * U)$;
- **else** payoff$_{decline} \leftarrow (1 - p)(R(t) * U)$;
- return payoff

Algorithm 3: Decision Making Algorithm for WDN

Input : pressure flow for each junction and link
Output: control setting for valve and pump

- **if** *flow > normal range* **then**
- close pump ;
- **else** open pump ;
- **if** *pressure > normal range* **then**
- close valve ;
- **else** open valve;

IV. RESULTS AND DISCUSSION

In this section, a WDN network is developed in order to simulate the entire network and evaluate the proposed algorithms. A 24 hours demand pattern is presented to demonstrate the customer's need and control the networks accordingly. Following that, the overall system energy will be measured before and after applying the our proposed methodology. This section aims to present the WDN case study, and discuss the energy saving results.

A. *Case Study of WDN*

The simulation in this study employed a specific WDN model as an example to demonstrate the performance of our proposed method (see Fig. 4). The considered case study is simulated to show the problem we are aiming to tackle of having several customers and water supply resources (i.e., reservoirs). A simulation of five customer demands is run over 24 hours (see Fig. 5). The simulation findings show that the regions around the consumers have a high demand, which can have an impact on energy efficiency (see Fig. 5). Some customers may have many sources of supply to meet their water demand, and simulation tends to shift the flow through the valves in the event of overloading.

We presented all of the simulated parameters of the nodes (i.e., junctions, reservoirs, and tanks) and links (i.e., pipelines, pumps, and valves) to support the simulation parameters (see Tables I and II). These parameters are the water elevating in feat (ft), initial water demand in Gallons per Minute (GPM), current demand in GPM, and pressure in Pound per Square Inch (psi) for the node parameters, and Flow in GPM and status for the water links. The junction, reservoir, and pipeline abbreviations are Junc, Resvr, and Pipe, respectively. In the EPANET specifications, the negative sign represents the reverse representation. For example, when a pipeline has a negative flow measurement, it indicates that it flows in the other way (e.g., Pipe 8, 15, etc...); similarly, when a reservoir has a negative demand measurement, it indicates that it must supply this amount (e.g., Resvr 1, 9 and 8). Some of the junctions appear to represent customers: for example, Junc 12, 4, 5, 3, 5, and represent Customers 1 to 5, respectively. The variance in demand is determined by the amount of water used by the customers.

TABLE I: WDN Nodes specifications of the junctions and tanks

Node ID	Elevation (ft)	Base Demand (GPM)	Demand (GPM)	Pressure (psi)
Junc 7	600	0	0.00	169.73
Junc 3	700	80	40.00	129.99
Junc 6	500	20	10.00	216.65
Junc 4	500	75	37.00	212.37
Junc 5	600	50	25.00	167.20
Junc 12	600	30	15.00	171.50
Junc 13	0	0	0.00	428.43
Junc 14	0	0	0.00	430.48
Resvr 1	1000	#N/A	-3442.32	0.00
Resvr 9	1000	#N/A	-2289.76	0.00
Resvr 8	1000	#N/A	-1676.96	0.00
Tank 2	850	#N/A	2453.40	52.00
Tank 10	850	#N/A	2267.80	52.00
Tank 11	850	#N/A	2560.07	52.00

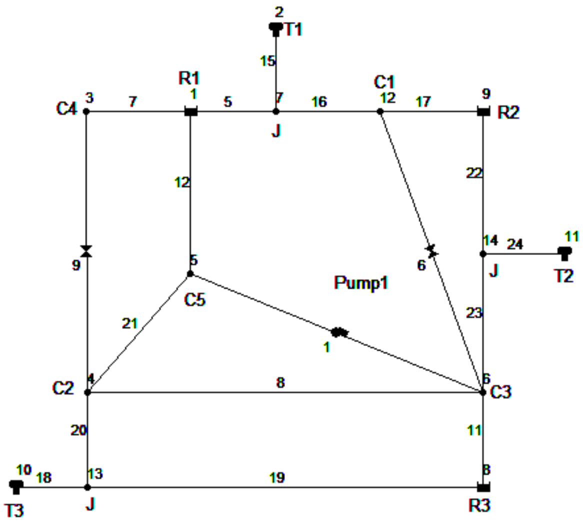

Fig. 4: Proposed WDN Case study

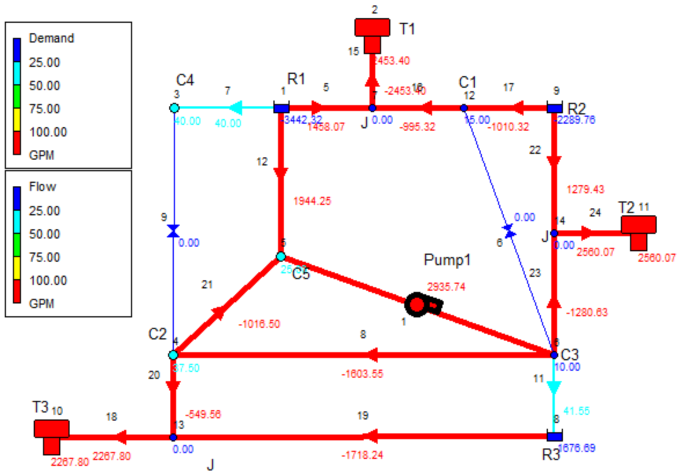

Fig. 5: WDN simulation with varying demand using EPANET.

TABLE II: WDN Links specifications of the pipelines & valves

Link ID	Flow (GPM)	Status
Pipe 5	1458.07	Open
Pipe 8	-1603.55	Open
Pipe 11	41.55	Open
Pipe 15	-2453.40	Open
Pipe 16	-995.32	Open
Pipe 17	-1010.32	Open
Pipe 18	2267.80	Open
Pipe 19	-1718.24	Open
Pipe 20	-549.56	Open
Pipe 21	-1016.50	Open
Pipe 22	1279.43	Open
Pipe 23	-1280.63	Open
Pipe 24	2560.07	Open
Pipe 7	40.00	Open
Pipe 12	1944.25	Open
Pump 1	2935.74	Open
Valve 6	0.00	Closed
Valve 9	0.00	Closed

The demand pattern for each customer from C1 to C5 in the 24 hours is adjusted in EPANET as a multiplier for each initial base demand customer shown in Fig. 6 as the base demand of junction 12 (C1) is 30 GPM, junction 4 (C2) is 75 GPM, junction 6 (C3) is 20 GPM, junction 3 (C4) is 80 GPM and junction 5 (C5) is 50 GPM [12].

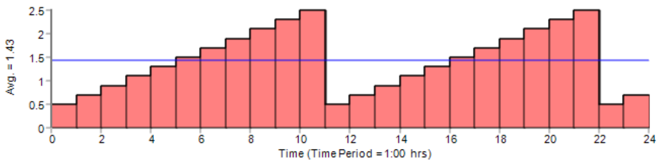

Fig. 6: Demand pattern

B. *Energy Saving Results*

Table I demonstrates the energy-saving where Hr. is hour slot, D1 is total Demand before optimization, D2 is total Demand after optimization, Resvr is the reservoir pattern, T is tank pattern, P/V is a pump and valve pattern as the following (valve1,valve2,pump), E1 is total energy before optimization, E2 is total energy after optimization and R is Energy saving ration per time slot where the negative sign indicates that the tanks were filled. As the table shows, the maximum energy saving was at the first time slot with a saving ratio of 60.86%. The results also demonstrate that the saving ratio per day was 13.39% which calculated using the following equation

$$Ratio_{day} = (\sum_{i=1}^{24} E1(i) - \sum_{i=1}^{24} E2(i) / \sum_{i=1}^{24} E1(i)) * 100 \quad (3)$$

where $Ratio_{day}$ is the total Energy Saving ratio per day,i is the time slot, $E1_(i)$ is the total energy consumption before optimization per time slot, $E2_(i)$ is the total energy consumption after optimization per time slot

Fig. 7 demonstrates comparison between the Energy Consumption before and after optimization where E1 is total energy before optimization per time slot, E2 is total energy after optimization per time slot

TABLE III: Energy Saving Results

Hr.	D1	D2	Resvr.	T	P/V	E1	E2	R
0	7644.55	7408.8	(1,1,0)	0	(0,0,1)	56.82	34.58	60.86%
1	6165.56	5996.9	(1,1,1)	1	(0,0,1)	36.65	15.69	57.19 %
2	4690.74	4633.4	(1,1,1)	0	(0,0,1)	23.92	20.09	16.01%
3	3258.01	3282.65	(1,1,1)	1	(0,0,1)	17.4	14.38	17.37 %
4	1689.93	1877.74	(1,1,1)	0	(0,0,1)	14.72	17.01	-15.56%
5	533.56	382.5	(1,1,1)	1	(0,0,1)	14.69	14.59	0.68%
6	351.02	3390.34	(1,1,1)	0	(0,0,1)	14.66	15.53	-5.93 %
7	524.73	484.5	(1,1,1)	0	(0,0,1)	14.83	14.81	0.13 %
8	492.98	535.5	(1,1,1)	1	(0,0,1)	14.89	14.92	-0.20%
9	601.61	586.5	(1,1,1)	0	(0,0,1)	15.04	15.03/	0.07%
10	611.54	637.5	(1,1,1)	0	(0,0,1)	15.13	15.15	-0.13%
11	270.43	127.5	(1,1,1)	0	(0,0,1)	14.16	14.09	0.49%
12	76.8	178.5	(1,1,1)	0	(0,0,1)	14.15	14.18	-0.21%
13	293.96	229.5	(1,1,1)	0	(0,0,1)	14.31	14.28	0.21%
14	215.99	280.5	(1,1,1)	0	(0,0,1)	14.35	14.38	-0.21 %
15	369.16	331.5	(1,1,1)	1	(0,0,1)	14.5	14.48	0.14 %
16	337.49	703.53	(1,1,1)	0	(0,0,1)	14.57	14.83	-1.78%
17	454.65	433.5	(1,1,1)	0	(0,0,1)	14.71	14.7	0.07%
18	452.59	484.5	(1,1,1)	1	(0,0,1)	14.79	14.81	-0.14%
19	545	456.12	(1,1,1)	0	(0,0,1)	14.92	14.87	0.34%
20	563.86	586.5	(1,1,1)	0	(0,0,1)	15.02	15.03	-0.07 %
21	638.66	637.5	(1,1,1)	0	(0,0,1)	15.15	15.15	0 %
22	256.93	127.5	(1,1,1)	1	(0,0,1)	14.15	14.09	0.42%
23	80.49	311.65	(1,1,1)	1	(0,0,1)	14.15	14.25	-0.71%
24	292.04	134.61	(1,1,1)	1	(0,0,1)	14.31	14.24	0.49%

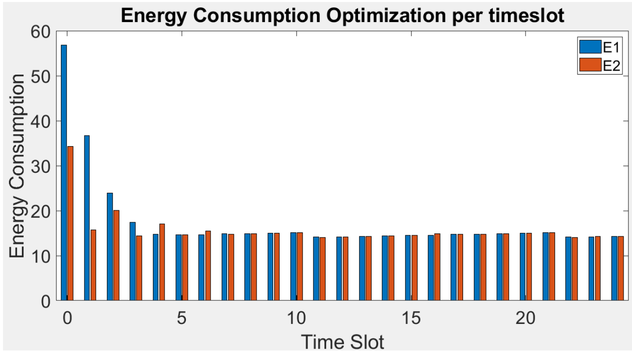

Fig. 7: Energy before and after Optimization

V. CONCLUSION

The work presented in this paper employs the optimization of energy consumption using various methods, including a genetic algorithm to optimize the tank demand pattern. An approach for integrating MATLAB and EPANET in integrated modeling of intelligent WDNs, which use intelligent decision support to manage the quantity and quality of water, was described and presented. In cyber networks, we use game theory to decide how to control the actuators on the physical network represented by EPANET. This study shows that energy consumption can be reduced by using electricity during low-cost hours to fill storage tanks for use during peak hours. The energy consumption changes over time, causing the largest energy cost savings after optimization was 60.86 % over hour slot and 13.39 % where saved per day.

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