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Street Lighting and Charging Stations with PATs Location Applying Artificial Intelligence

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Abstract: This research proposes a methodology with multi-objective optimization for the placement of Pumps operating As Turbines (PATs), energizing street lighting, devices for monitoring the water network, and charging stations for small electric vehicles such as bikes and scooters. This methodology helps to find the most profitable project for benefiting life quality and energy recovery through pumps operating as turbines, replacing virtual pressure reduction valves to locate the best point for decreasing pressure. PATs are selected by maximizing power recovery and minimizing pressure in the system as well as maximizing recoverable energy. Benefits analyzed include the reduction of carbon dioxide emissions and fuel use, as well as the saving of electricity consumption and benefiting socio-economic impact with street lighting, monitoring, and charging station. It was considered that each PAT proposed by the methodology will supply a street light pole, a station for monitoring the water network, and a charging station; under these established conditions, the return on investment is up to 1.07 at 12 years, with a power generation of 60 kWh per day.

Keywords: renewable energy; distributed energy generators; multi-objective optimization; socio-economic analysis

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1. Introduction

Exponential urban growth increases energy demand with the application of recent technologies such as internet of things and new concepts such as smart cities related to data acquisition, storage, and usage. For a long time, fossil energies were employed as the sole source of power. Currently, the focus is on clean energies; thus, PATs have been studied as an alternative system to recover energy in pressurized systems [1], enhancing efforts for sustainability cities [2–4].

This article aims to propose a socio-economic study as a decision factor to locate PATs in Water Distribution Networks (WDN) finding viability between economic and societal benefits according to the placement of PATs. The study focuses on maximizing the Return on Investment (ROI) while ensuring the required pressure in the water network. However, the socio-economic benefits are related to the use of PATs for urban lighting, micro-generators of electricity to power monitoring devices to monitoring pressure and even security equipment such as cameras and charging stations.

The PATs placements focus on the major electricity generation; however, the present study tries to focus on small Distributed Generators (DGs) reducing power losses on distribution [5,6]; unlike grid-connected systems they can be installed at each consumer node which implies a great number of configurations. Thus, this presents a challenging combinatorial optimization problem, such as the one presented in the challenge of locating DGs off-grid on the electrical network to supply electricity to houses [6].

1.1. Environment Impact

Climate change effects are more noticeable each year with impacts on human health and nature systems. United Nations called for a plan of 17 Sustainable Development Goals (SDG), which encompasses strategies reinforcing social, economic, education and health aspects while tackling climate change [5]. This plan was presented in the General Assembly "Transforming our world: 2030 Agenda for sustainable development" with the objective of reaching these targets before 2030. The SDG can be used as a tool in local governments to create innovative policies, and it recommended partnerships within public and private sector as a key towards sustainable development enhancing the intermediary roles between these two sectors [7].

The SDG mostly focus on human wellbeing, as seen in most of the targets. However, there are objectives aimed to combat climate change and preserve nature systems and, consequently, to reduce the impact of human activities. SDG number 7 (SDG-7) aims to improve the energy system toward sustainability, where mainly investment participation by the private sector is more visible in low and middle income countries and distance between actors and action-outcomes obstructs accountability, while high income countries have high readiness in meeting the SDG targets, such as Iceland, Norway and Sweden which lead in energy sustainability aspects [4,8,9]. It was observed that SDG-7 depends on others SDGs related to environmental and economic concerns [10].

The relationship between society and the private sector is often defined by the acquisition and payment of services such as water and electricity. This relationship plays a key role in improving the water supply, as both water and electricity organizations focus on sustainable development using clean energy. In turn, society tends to respond more positively to payments from companies that are socially responsible and that enhance trust. This is evident in the higher payment collection rates observed from these types of companies.

To improve their operations and better serve their customers, water distribution companies often employ various technologies and systems, such as the Supervisory Control and Data Acquisition (SCADA) system. SCADA systems are used to manage and optimize water distribution networks, and typically include remote monitoring and control systems, data storing and analysis of consumption data, and other features that help companies optimize their operations. By utilizing these and other technologies, water distribution companies can improve their approaches towards society and more effectively meet the needs of their customers in a rapidly changing world with increasing energy demands.

The impact of the energy sector on climate change, and vice versa, should be considered in relation to adaptation to a changing environment and mitigating greenhouse gas emissions. To address the challenges of smart cities and sustainable development, it is important for water distribution companies to engage with society and assess common interests. This may involve working to minimize the environmental impact of water distribution systems, adapting to changing climates, and addressing the interrelated impacts of climate change and the energy sector. For example, as global temperatures rise, there is likely to be an increased demand for electricity for cooling spaces, particularly in hot, humid, low-latitude areas. In Japan, studies have projected a 14.2% increase in nationwide electricity demand during hot seasons. It is important for water distribution companies to consider these and other factors when developing their strategies towards society [11].

One of the actions to combat climate change is the use of renewable energies. This paper evaluates the reduction of CO_2 emissions through the implementation of PATs to utilize renewable energy for various purposes. However, in Mexico, different barriers to a clean energy transition and access to a vast oil and gas resources in the past reinforced the position of fossil-fuel incumbent regimes. This shifts the technology niches away from clean energy. Previous points continue to displace investment in research in clean energy, development, and innovation in Mexico. Policy paradigms have shifted based on (dynamic) societal needs and socio-political interests in favor of fossil fuel power generation, especially in developing countries [12].

Water Utilities Companies (WUC) face the challenge of increasing infrastructure to satisfy the growing water demand of rapidly growing cities, so new water distribution tanks and water pumps for extraction and redistribution of this vital liquid must be built up. Energy consumption by water pumps results in higher cost for WUC; this problem translates to higher prices for drinking water users, as water tariffs increase. High energy tariffs were reflected towards in drinking water tariffs. In 2013, operating agencies reported an expenditure between 23.9% and 71.7% for the payment of electricity on the total amount of money destined for consumption of goods and services. During 2013, Mexican legislation implemented changes to electricity policies that resulted in the transformation of the type of electricity rate for WUC from public service rates to rates applied for industries. These changes have had a lasting impact on various WUCs, with some becoming financially unsustainable as a result [13].

1.2. Aims of the Study

The minimum pressure in the WDN established by the regulatory WUC is a key factor in ensuring service to customers by maintaining an appropriate water flow. The pressure of water in a pipe is affected by various factors, including fluid velocity and height. However, when the pressure head is higher than minimum pressure in network pipes, there is an excess of energy. This energy excess will vary over time, since the demand in the network is not constant, the pipe flow and pressure in the nodes is affected. However, this energy excess is often needed to ensure minimum pressure in further nodes [14]. This work aims to analyze the benefits of implementing PATs in the water distribution network in Guanajuato, Mexico, including the benefits of using the excess energy generated by the PATs to power street lighting and other connected devices such as monitoring devices and charging stations.

1.3. Structure of the Study

The paper is organized as follows: in Sections 2.1 and 2.2, concepts of PATs selection and optimization techniques are described. Section 2.3 describes the implementation of the optimization technique for the problem formulation, including the objective function and constraints (Sections 2.3.3 and 2.3.4). In Section 2.4, the water distribution network and the general conditions for the analysis are described. In Section 3, the proposed locations of PATs for the WDN and a socio-economic study are presented, highlighting the benefits of PATs such as street lighting, monitoring the water network, and charging stations.

2. Materials and Methods

2.1. Pumps as Turbines

Different research projects have focused their investigation on energy recovery in pressurized water systems. One of the energy recoveries is through the application of PATs [14–17]. Williams et al. [17] proposed substituting Pressure Reduction Valves (PRV) to recover the energy dissipated in the valves, generating significant electric savings.

The PATs are more economically feasible than turbines due to the wide range in pumps models. The ease of procurement and gathering spare parts, as well as the availability of trained manpower, are important factors to consider [18]. Benefits reached by the PATs show lower efficiency in the management in flow and head rate drop variables, however, this aspect can be improved through diverse mechanisms of electrical and hydraulic regulations [19–21].

Many authors have conducted research on the analysis of experimental and numerical models to generate predictive models for different PATs devices [22–29]. These authors focus on the correlation calculation of the Best Efficiency Point (BEP). The BEP can be obtained through empirical models or 1D models with known and unknown geometry, 2D models, and 3D models with Computational Fluid Dynamics (CFD). This work uses the empirical results from diverse authors to obtain PATs characteristics curves. The curves are chosen based on the hydraulic data and match with previous studies. If the operational curves of the pumps are not known, the hydraulic power will be estimated using the BEP, the fixed flow, and head.

Most suitable PATs are found through diverse methods employing BEP for flow rate, C_Q (Equation (1)) and head rate, C_H (Equation (2)).

$$C_Q = \frac{Q_{BEP_t}}{Q_{BEP_p}} \quad (1)$$

$$C_H = \frac{H_{BEP_t}}{H_{BEP_p}} \quad (2)$$

where Q_{BEP_t} refers to the BEP for flow rate in turbine, Q_{BEP_p} refers to the BEP for flow rate in pump, H_{BEP_t} refers to the BEP for head in turbine, and H_{BEP_p} refers to the BEP for head in pump.

$$n_q = n\frac{\sqrt{Q}}{H^{3/4}} \quad (3)$$

where n_q is the specific speed of device working as pump or PAT in revolutions per minute (rpm) and refers to the speed at which a device (such as a pump or PAT) operates when it is working at its BEP; $Q\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$ is the flow rate, $H(\mathrm{m})$ is the head, and $n(\mathrm{rpm})$ is the rotational speed calculated for BEP mode.

Obtaining characteristic curves for operational PATs requires knowledge of the BEP when running in turbine mode, and when program analysis comes in terms of many numbers of PATs, it may be inconvenient to study each pump because of lack of time or computational resources. As a result, diverse authors developed methodologies for selecting PATs.

The Reduction Energy Dependency in Atlantic area Water Networks (REDAWN) has made a database that contains the main geometric performance characteristics curves of 34 different centrifugal pump models previously studied [27]. There are four types of provisions studied [30]; 20 End Suction Own Bearing (ESOB) devices, 7 Multi-Stage Vertical (MSV), 6 Multi-Stage Horizontal (MSO), and 1 Multi-Stage Submersible (MSS). Different equations (Equations (4)–(7)) were developed through regression analysis of multiple operating curves of the aforementioned PATs, as described by Fontanella et al. [27], in the REDAWN project.

$$n_{st} = 0.8793 n_{sp} \quad (4)$$

where n_{st} is the specific speed for the PAT, while n_{sp} is the specific speed for the pump; this relation is stablished by [27] within a linear expression using PATs database from REDAWN [1,29], the Equation (5) is valid for 0.2658 < N_t/N_p < 1.2828, thus, PAT study will be calculated with the BEP analysis. N_t (rpm) represents the rotational speed of the turbine and N_p (rpm) represents the rotational speed of the pump.

$$\frac{Q_{BEP_t}}{Q_{BEP_p}} = 1.3595\frac{N_t}{N_p} \quad (5)$$

$$\frac{H_{BEP_t}}{H_{BEP_p}} = 1.4568\left(\frac{N_t}{N_p}\right)^2 \quad (6)$$

$$\frac{P_{BEP_t}}{P_{BEP_p}} = 1.0403\left(\frac{N_t}{N_p}\right)^3 \quad (7)$$

2.2. Real Coded Genetic Algorithms

Genetic Algorithms (GAs) are inspired by the principle of natural selection in evolution by Darwin [31] (Figure 1). The process begins with the creation of a population which contains multiple solutions to a problem, and each solution is called an individual. This individual may have restriction values to refine the search for a solution. An individual has a vector of bits, referred to as chromosomes, which can undergo mutation and exchange bits of genetic material with other individuals through a process called recombination or crossover. This creates new individuals with a combination of traits from the parents. Each member in population is qualified by an Objective Function (OF). The OF represents a mathematical formulation to the problem and the solution. OF may have only one objective or multiple objectives. After evaluating individuals with the OF, the objective passes on through a selection process (roulette, tournament, etc.), and crossover process (two points, one-point, multiple points, etc.) to birth new individuals in a new population. By starting with a large population and using processes such as mutation and crossover to explore a wide range of solutions, it is less likely that the algorithm will get stuck in a local minimum, where it finds a solution that is not optimal but cannot find a better one. However, it is important to keep in mind that increasing the size of the population also increases the computational resources required to run the algorithm. Each new generation should be better than the old one [32–34]. GAs are widely applied to solve problems in the hydraulic area, due to the ease of their implementation [34–42].

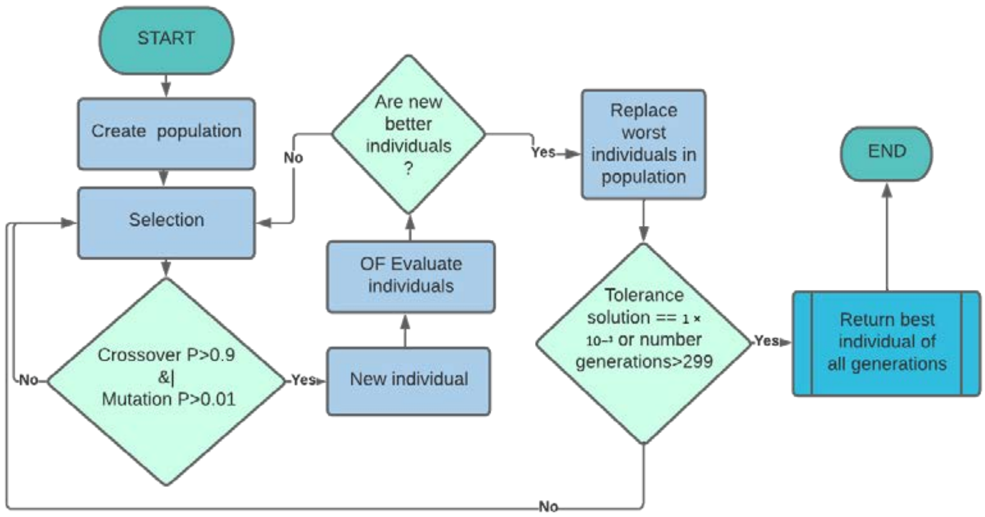

Figure 1. General process of GAs.

Real Coded Genetic Algorithms Application

Real Coded Genetic Algorithms (RCGAs) represent genes as real numbers, the size of the chromosome is a vector of floating points numbers (Figure 2) that represents the vector of the solutions in the problem, therefore, the search space and coding have no difference. RCGA gradually solve functions with continuous variables. The graduality refers to the sensitivity of the function to small changes in the variables. This approach allows more precise and fine-tuned adjustments in the search for optimal solutions [43].

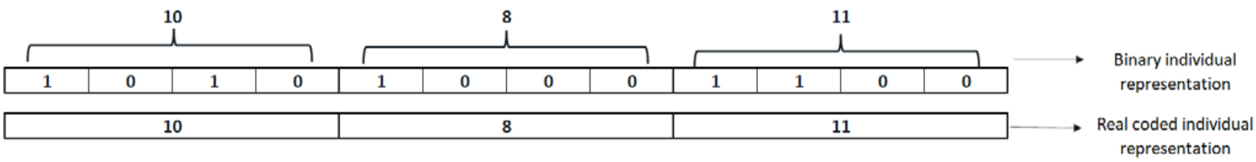

Figure 2. Individual representation of RCGA and GA. Upper, the binary representation of viable solutions. Down, viable solutions represented by floating numbers.

The solutions are proposed with RCGA, where random individuals are generated, taking place on each link available to locate a PRV (Figure 3); this procedure consists of editing the original network by adding an intermediate node between original nodes of the link and adding a PRV which would represent a PAT due to pressure reduction. The simulation results are then used to evaluate the performance of the modified network in terms of pressure reduction, PRV set point values, and head loss. This information is likely being used to determine the feasibility and efficiency of using PRVs to recover energy from the network as PATs.

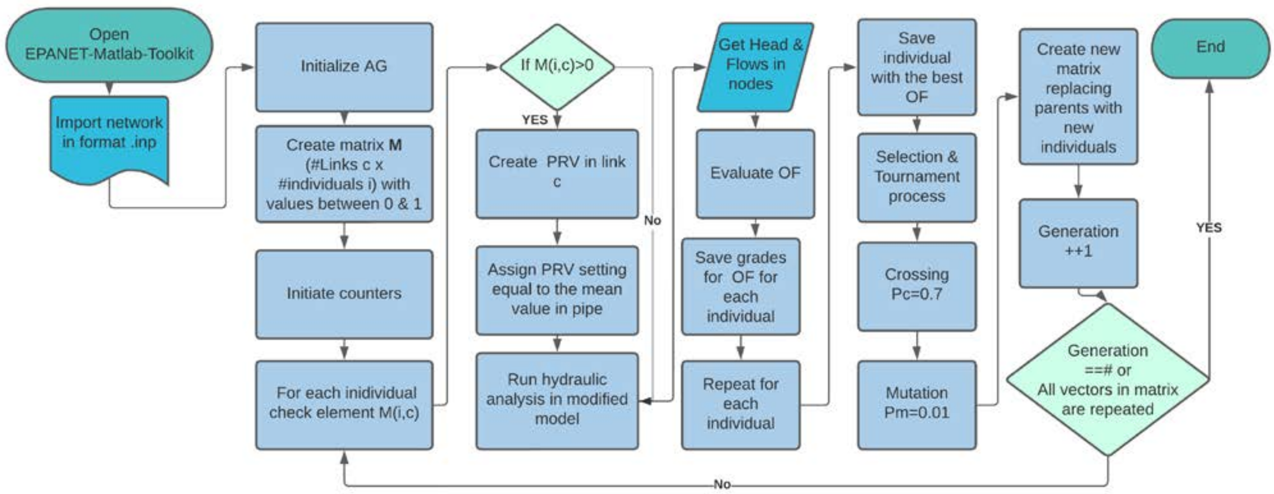

Figure 3. RCGA process for diminishing Head & Pressure. Where # is number and ++ means plus one, and == means conditional if equal to.

In this case, the solution is represented as 1 for a node which has a PRV and 0 for those that do not have a PRV. A random value between 0 and 1 is generated to create the population using a uniform distribution, employing MATLAB's 9.10 (R2021a) *rand* function. If the generated value is greater than 0.7 the value is set to 1, otherwise it is set to 0. The value of 0.7 means that algorithm simulates PATs with maximum 30% of individuals in order to obtain an optimal solution with practical number of PATs along the WDN. Crossover and evolutionary process would increase or decrease the number of PRV necessary to guarantee functionality and improving qualifications of the OF through generations.

As an example, a network can be considered which has twelve pipes in its configuration. The individuals are randomly generated and they might contain a PRV, or not (Figure 4). In the case of having a PRV, a value setpoint would be assigned. It is observed that Pipe 1 and Pipe 6 contain a PRV for the first generated individual, and there are variations for everyone into the population.

Pipe / Individual	1	2	3	4	5	6	7	8	9	10	11	12
A	1	0	0	0	0	1	0	0	0	0	0	0
....	...	...	...	...	...	...	...	...	...	...	...	...
AA	0	0	1	0	0	0	0	1	0	0	1	0

Figure 4. Example of individuals generated by RCGA. Green color for Individual A and blue color for individual AA.

Crossover is performed using two points. These points are selected within the length of the individuals; as an example, the two points' crossing takes individual A and AA from Figure 4. To generate two new individuals, as shown in Figure 5, these individuals enter a tournament to replace the two worst individuals in the initial population. The probability of crossover (meaning the probability that two individuals will exchange genetic information to create offspring) is 0.7. Randomly, a gen is selected and has a chance of mutating of 0.01. These mutations and crossing probabilities are selected from previous studies which showed a good behavior, subsequently used as conventional values [44].

Individual	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Pipe 7	Pipe 8	Pipe 9	Pipe 10	Pipe 11	Pipe 12
New 1	1	0	0	0	0	0	0	1	0	0	0	0
New 2	0	0	1	0	0	1	0	0	0	0	1	0

Figure 5. Two points crossing The colors indicate the genes crossing for the new individuals.

2.3. Problem Formulation

The local WUC in Guanajuato has established a minimum pressure requirement for the WDN to ensure that customers receive reliable service. According to the regulatory department, this minimum pressure is set at 5 mwc. When the head (pressure) in the WDN is higher than the minimum pressure in critical nodes, it means that there is excess energy in the system. The WUC can take advantage of this excess energy by using it for other purposes, such as generating electricity. Maintaining sufficient pressure in the WDN is essential to ensure that water flows properly through the system and reaches all customers. This excess of energy will vary over time since the demand in the network is not constant, so the pipe flow and pressure in the nodes is affected [45]. However, this excess of energy is often needed to ensure minimum pressure in further nodes [14]. Using this excess of energy through PATs aims to dissipate and transform the potential hydraulic energy into electrical energy. The efficiency coefficient η used in this study was assigned a constant as 0.65 [46,47], and this coefficient has been used to determine the optimal placement of PATs.

Optimal placement of PATs is proposed, aiming to select the best operational PAT utilizing models database from the REDAWN project, with the characteristics operational curves hydraulic and power provided. The placement of PATs maximizes return of investment while improving the energy supply to measure, register and security devices strengthening socio-economic factors for surrounding population to the project.

Program setting is based on following assumptions:

- Prices are adjusted according to the annual inflation rate of the place of origin study and transferred to Mexico.
- Design period is 15 years.
- Street lighting, monitoring equipment and charging stations are installed around the location of the PAT.
- Database of characteristic curves for PATs are available.

The main process is developed using EPANET-Matlab-Toolkit [48] to locate the profitable excess of pressure. The network is imported to MATLAB 9.10 (R2021a) with the mentioned toolkit in "inp" format, then all necessary data are taken from the network. The next process involves the use of RCGA and proposes multiple PRV with different setpoints values for each link on the net. There is the possibility that no PRV is presented in different pipes except those which connect reservoir, tanks, and pumps. Then, the hydraulic analysis is simulated: pressure in nodes, setpoint values, PRV number are the main output in each generation to calculate the OF. The OF has the objective to reduce the pressure in the node with the highest initial pressure but guaranteeing supply and pressure at all hours during the simulation for every node while also minimizing the number of PRV. The main methodology is composed of three general steps showed in Figure 6.

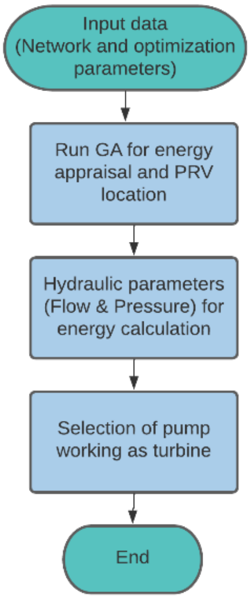

Figure 6. Overview of the methodology.

The purpose of the PRV is to locate the links where it is more profitable to install a PAT. The PRV itself does not represent a PAT, but it helps to identify the optimal locations for the PATs installation. Those optimal locations must generate sufficient pressure and energy to meet the specific needs of each location, as well as being cost-effective and able to operate efficiently under the local conditions according to the next three cases.

Case 1: There is an excess of pressure that can be used to generate electrical energy, but energy cannot be stored in batteries, so it is redistributed to the electrical utility and sold. (Adds portage fee, and electrical sale)

Case 2: Energy is enough to feed lighting, monitoring, and charging stations, but there is no sale to the electrical utility. (Installation of batteries there is functional all the time)

Case 3: Energy is minimal and barely feeds light poles and monitoring equipment (There are no charging stations for electrical mobile devices).

The Benefits considered by the installation of PATs are focused on energy recuperation. Furthermore, this study considers the benefits of implementing water monitor and lighting equipment around the installation project, so the economic benefits are listed:

1. Diminish in network due to water pressure reduction: Leakage Reduction (LR). Leakage in WDN is related to high pressure, thus, diminishing pressure would reduce the quantity of water losses and new leakages. The energy cost for pumping and extraction in 2019 for Guanajuato is USD $0.10/m^3$, while the energy consumption for water treatment is around USD $0.38/m^3$ [49]. Furthermore, approximately 45% of the water in the distribution system is lost and not billed, which is an indirect measure of the commercial efficiency and operation of the water systems. Based on the industrial tariff of electricity at USD $0.10/kWh, the energy consumption is calculated based on the estimated leaks in the system according to the measured volume [49]. Previous studies have shown that reducing pressure in the water supply system can effectively reduce leaks of potable water between 3% to 31% [47,50,51]. In this study, a 3% reduction in leakage was considered as the worst case, where there is minimal improvement in the WDN.
2. Reduction of Environmental Impact (EI). EI costs from CO_2 emissions are caused by electricity transport, production, and supply. These costs are obtained from literature and, thus, actualized with annual inflation. The EI comes from the misuse of fossil fuels for producing electricity; it is estimated that pollution derived from CO_2 emissions have a cost of 17.87% of the electricity transport, production, and supply [52]. Mobile electric vehicles such as bikes or scooters can be used to travel short distances;

these vehicles promote and spread green culture and generate satisfaction among citizens [2,53]. Employing electric vehicles reduces the use of fossil fuels over time. A diesel car emits 0.133 $kgCO_2$/km [54], and this could potentially be reduced by 14.56 tons of CO_2 within a year if 100 people used electric bikes or scooters instead of cars for trips at least 3 km in length [2,55,56]. These vehicles could be powered by multiple distributed generators in urban areas, and fuel consumption could be reduced by approximately 5110 L/year, as described by Ramos et al. [2].

3. Electric Savings (ES) from producing-consuming electricity in situ. Electricity consumed from devices to monitoring pressure on the network, security equipment and charging station are listed in Table 1. This consumption is evaluated as if it were demanded from the national electrical network, using electrical tariffs [57] respect to consumption. The porting fee savings is a cost that is charged to energy producers for using the electrical networks of the Federal Electricity Commission (CFE in Spanish) considering that the connections would not be made in low voltage saves the charge $0.045 USD per kWh [58]. In this case, the PAT works like a dynamo with direct current that is directed to a battery and after the various equipment. As drinking water treatment energy cost are integrated in consuming electrical bills, the loss of water due to leakage reflects a loss in energy and an increase in CO_2 emissions.
4. Crime and accident reduction derived from street lighting: Street Lighting (SL). This methodology aims to transfer into economic terms the benefits derived from urban lighting. The purpose of urban lighting is to improve visibility in the streets when the sun goes down, in this way, pedestrians and vehicles have better visibility of the road for their displacement and, thus, avoid accidents [59]. In the same way, lighting can prevent the occurrence of crime. It is estimated that public lighting consumes the equivalent of 2.25% of the national electricity consumption. This analysis will focus on the economic valuation of the savings in the reduction of the rate of road accidents in an illuminated area to an unlit area during from dusk to dawn. On the other hand, the decrease in the crime rate under the same conditions of the previous analysis.

Table 1. General equipment characteristics.

Equipment Name	Energy Characteristics	Description
Streetlamp	50 W	7100 Lumens model H9996
Pressure registers and transmitters	0.64 W	EDSX-995d
Security camera	7.2 W	Tapo C200 V2 online security camera with nocturn vision
Set of batteries within electrical transformer and converter for the charging station.	12 V batteries each Capacity at least of 35 kWh 9 kW converter Maximum output of 4kW	Major description can be found in previous study by Ramos et al. [2]

2.3.1. The Cost of Installing Street Lighting, Monitoring Devices, and Charging Stations

The cost refers to the value of consuming a good or service [60]. The investment costs refer to all those costs due to the acquisition of material, as well as that required for its construction to an operational point. The concepts are on-site supply of the elements, civil works, assembly, engineering, construction management, supervision, regulatory, financial.

The costs estimated by Ramos et al. [2] calculate an initial cost of employing charging stations with lead-acid batteries $16,584.28 USD from 2021 to 2022 employing an inflation rate of 1.3% [61]. Lead-acid batteries are considered the best option according to the cited study.

The costs estimated to renovate lead-acid batteries are $131.29 USD/kWh. Including benefits related to the environmental impact, recycling, and waste disposal [2,62]; $4608.56 USD are considered every six years for the renovation of batteries.

The cost per unit for a streetlight with a pole is $1454.33 USD [63–65]. Data from 2019, calculating the accumulated inflation to 2022 with 16.87%, the cost was updated to $1699.68 USD. This cost includes the installation of a new street pole on the street, which is necessary in Guanajuato streets that are considered deficient in street lighting according to surveys conducted by INEGI [66]. If the installation exists, this cost must be omitted.

The maintenance costs are those to preserve and/or repair the equipment for a correct operation. An average cost for maintenance of one street light pole is $26.15 USD [67].

2.3.2. Benefits of Street Lighting (SL)

Previous studies have economically valued the benefits of public lighting, assigning a value to traffic accidents due to material damage, injury, or fatalities, where insurance typically provides compensation [68]. Under economic terms, the reduction of road accidents represents an economic benefit. The cost of a road accident varies depending on the damage and type of accident. Studies conducted in Argentina calculate the cost per road accident average as $16,473.11 USD [68]. For this study, the average cost of accidents will be updated based on the inflation rate in Argentina 54.07% [69] and a value of $23,035.99 USD was obtained for 2021. In Mexico, 42.38% of accidents occur during the night, in which only 0.366% had a streetlight in the area of the accident [70]. Based on the previous report, in Mexico, the balance for material damage by accident is $4823.22 USD.

The benefit will be obtained from the formula developed by Manzano [68] and it was modified in this research, obtaining the Equation (8). The probability factor is implemented in equation to represent the chances of occurring a vehicle incident during the year, based on statistical local events.

$$B = 365(\times)C_{acc}(\times)TNMD(\times)T_R(\times)P_{accp} \tag{8}$$

where B is the economic benefit for the reduction of accidents due to the streetlight, C_{acc} is the average cost for damage to vehicles during an accident, $TNMD$ is the average daily night traffic on the road where the streetlight is placed, T_R is the accident reduction rate with the use of streetlight, P_{accp} is the probability in which the same number of accidents will occur as the average daily accidents in Mexico referred to in [63].

The accident reduction rate is calculated as the ratio of day and night accidents.

$$T_R = \frac{T_N}{T_D} \tag{9}$$

T_R is the rate of reduction of night accidents, T_N is the rate 0.424 of night accidents, T_D is the rate 0.736 of accidents that occur in the day and afternoon [70].

It is considered that the sun, with the time zone of central Mexico (GMT-5), rises at 7 am and sets at 19 pm. During the summer (the season of the year in which the road capacity was made). The average daily night traffic is 1348 vehicles in a capacity from Monday to Sunday; the maximum capacity recorded occurred during Friday with 3021 vehicles at 7 pm and the minimum on Tuesday at 4 am [63] within a road [60]. For this study, a scenario where no matter the type of road a vehicle passes on average daily during the night was considered.

On average, 43 traffic accidents occur per day, under this consideration we must add the probability of the 43 accidents occurring per day [71], so Poisson's probability is used, obtaining a probability of 6.07% that the event occurs. This probability must be considered when estimating the economic benefit in order to not overvalue the benefits.

For this reason, the annual economic benefit for the reduction and accidents is:

$$B = 365(\times)\$4823.22\ \text{USD}(\times)1(\times)0.736(\times)0.0607$$
$$B = \$78,649.59\ \text{USD}$$

In addition, another economically valuable benefit is reducing criminal events in the area, such as material damage to public and private property, as well sending a patrol to the area of the event in question. In terms of security, 56.2% of the population reported feeling unsafe on the streets they usually walk on and 54.8% considered the lighting insufficient, ranking second among city problems perceived by citizens [66]. The World Bank points to the lack of street lighting as a cause of feelings of insecurity, as criminals take advantage of the darkness to commit illegal acts [72]. The present study is limited to analyzing crimes in the common jurisdiction since, this type of crime is usually reported with an amount of value for damage or material loss although crimes such as murders, kidnappings, rapes are of high importance, human life is of incalculable value, as well as the feelings and psychological damages that may be caused to the affected person and their families that will not be quantified in this study [64,65,73,74].

Previous experiments in the United Kingdom used a control area with and without lighting in order to assess the economic benefits of lighting through a series of interviews with inhabitants of the pre- and post-lighting areas on streets where crime rates were reduced by up to 41–43%, among the statistical data of the costs are considered: burglary of home room, vandalism and robbery of passers-by and cars, threats, armed robberies, thefts of opportunity, among others. The average value per event is worth $1625.86 USD [65]. In Guanajuato, Mexico, 50,894 crimes were registered per 100,000 individuals per year while the national average is over 33,659 per 100,000 individuals per year, including robberies, armed robberies, extortion, fraud, theft of merchandise in transit, damage to facilities among others [75]. The municipality of Guanajuato, Gto., Mexico has a population of 186,450 [76], this data was updated using the population growth rate for 2020 with a value of 1.2 [77]. Based on the data, 94,892 annual crimes are calculated for the population of the city of Guanajuato; a total direct cost was calculated for the damages to the victims and those generated by the monitoring of the crime for a value of $154,280,884.38 USD.

2.3.3. Objective Function

The OF comprises two targets: (1) Increasing *ROI*, (2) Reducing Pressure in network. The function of *ROI* is considered a ratio between Benefits and Costs (Equation (10)). Thus, increasing *ROI* guarantees maximizing the Economic Benefits (*EB*) of implementing PATs on the network (Equation (10)). In this sense, the *ROI* can be considered an inverse relation between benefits and costs because as the costs of the investment increase, the *ROI* will decrease, and vice versa. The *EB* considered for the project is presented in (Equation (11)).

$$\text{Maximize } ROI = \frac{EB}{CO} \tag{10}$$

$$\text{Maximize } EB = LR + MI + SL + EI + ES \tag{11}$$

where *LR* is the Leakage Reduction, *MI* is the Mobile impact reduction, *SL* is the streetlight benefits, *EI* is the Environmental Impact reduction benefits, and *ES* is the Electric Saving, defined in Equation (12).

$$ES = \frac{1}{1 + |(ER - EP)|} \tag{12}$$

where, *ER* is the required energy by devices installed and *EP* is the produced energy by the PAT (Equation (13)).

$$EP(\text{kWh}) = \eta\gamma \sum H_{i,j} Q_{i,j} t_k \tag{13}$$

where H is the Hydraulic Head with the drop in pressure through the PAT, Q is the Flow passing through the PAT from node i to node j, at the time step k, γ is the specific weight of water ($\gamma = 9806 \ \frac{\text{N}}{\text{m}^3}$), η is the average efficiency of the PAT; in this case the minimum value described in literature is used, this allows considering the worst-case scenario when assigning PATs.

Total Costs (*CO*) can be minimized (Equation (14)). These costs are the sum of Costs of Investment (*COI*) plus the Costs of Maintenance (*COM*) and expenses in equipment acquired. Costs are obtained from literature and were actualized according to the inflation to 2022.

$$\text{Minimize } CO = COI + COM \tag{14}$$

The *COI* rely on the number of equipment installed (*NE*) and total price (*P*):

$$COI = NE * P \tag{15}$$

The *COM* from Operating and Expenses considered around 3% of the investment, for each electrical equipment, excluding batteries. The design period of the project is considered 15 years, and the lifetime of generic electrical equipment is around that period [3,78].

2.3.4. Constraints

The constraints for the main problem lie in water distribution. While pressure is reduced with PATs, WUC must always assure the availability of water for consumers, guaranteeing pressure and flow.

$$\sum Q_{i,j,t_k} = d_{i,j,t_k} \tag{16}$$

$$min\left(H_{i,j}\right) \geq 10 \text{ mwc} \tag{17}$$

With these constraints, several plans can be made to satisfy minimal water levels at tanks and consumer demand. This OF will be assessed for everyone in the RCGA population. Finally, the OF is related to Equation (10) where all factors of costs and benefits are involved, and Equations (16) and (17) must be satisfied as well.

2.4. Case Study

The methodology was implemented in a sector of the network of Guanajuato city, Mexico [79]. This network was chosen because of its information accessibility and previous studies related to optimization. In the study zone, flow rate and head range data were obtained from EPANET.

The methodology was implemented in a sector of the network of Guanajuato city, Mexico; the WCU is the *"Sistema de Abastecimiento de Agua Potable y Alcantarillado de Guanajuato" (SIMAPAG in Spanish)*. The sector of the network is known as sector 8–12 by the WDS. It is supplied by the water treatment plant: *"Los Filtros de Valenciana"* at around 2140 masl, whose source of supply comes from two dams, *"La Esperanza"* and *"La Soledad"*; located in the north part of the city. This sector includes nine neighborhoods (areas of the city near downtown) that include residential and commercial water consumers. The study area was chosen for its rugged topography (Figure 7), which increases the viability of energy use by PATs, as well as the population supplied by the WDS of approximately 34,000 inhabitants (approximately 22% of the 158,978 inhabitants supplied by the WCU [49]. This population is composed of a floating population of students, tourists, and also permanent residents. The hydraulic model is a calibrated scenario. The model calibrated is provided by SIMAPAG, and the calibration was performed with data collected from 1 digital flow meter and 30 pressure gauges installed throughout the WDN over a period of 1 month. The network model in EPANET was adjusted with the pipe roughness in the allowed range to obtain the nearest value of pressure measurements. The correlation with the means of the recorded data was 0.988, and the main characteristics are described in Table 2.

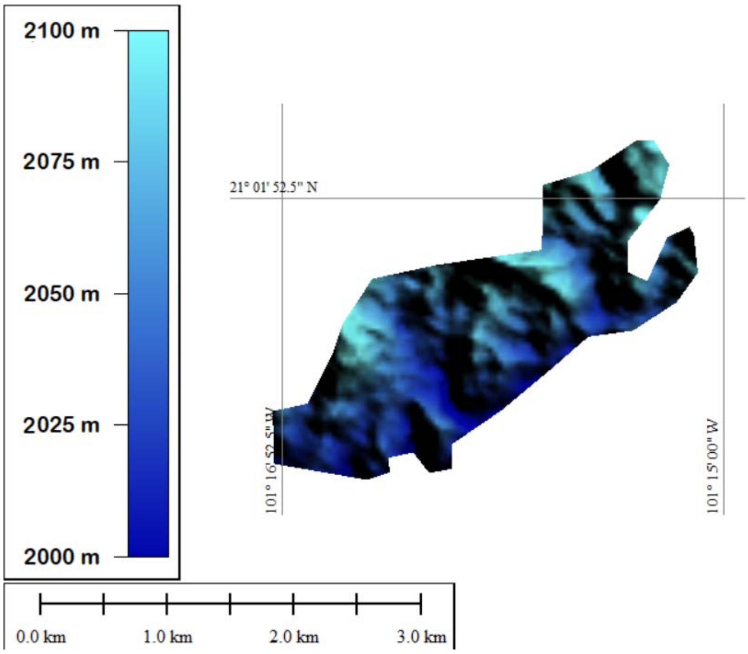

Figure 7. Topography in S8–12 Network.

Table 2. EPANET characteristics of the network.

Description	Parameters
Maximum consumption flow Elevation range (masl)	44.28 l/s 2042–2142
Reservoirs/Tanks	1/1
Total pipe length (m)	30,847
Pipe diameter range (mm)	50–600

3. Results

Applying the algorithm described in Section 2, the GA process proposes four points of pressure reduction located as the optimal solution: First, PAT 960 is located downstream Macrocentro in Dos Ríos suburb (green frame in Figure 8). Second and third, PAT 539 and PAT 70, near the middle of the network (blue and magenta frame, respectively). The fourth, PAT 813, is located at the south of the network (red frame); this zone has few habitants but is near a school. The PATs location in Figure 8 was the optimal solution based on a combination of factors, including the pressure in the network, the benefits for the population in the area and the potential for energy recovery. These factors were considered to identify the most suitable locations for implementing energy recovery systems in the network. The PRVs were used in Epanet to simulate the installation of the PATs. The pressure reduction with the PRVs obtained in the results of the optimal solution was used to define the PATs with entrance and exit pressure in order to produce the energy. Pressure data and the conditions of critical nodes affected for proposing the PATs are shown on Table 3.

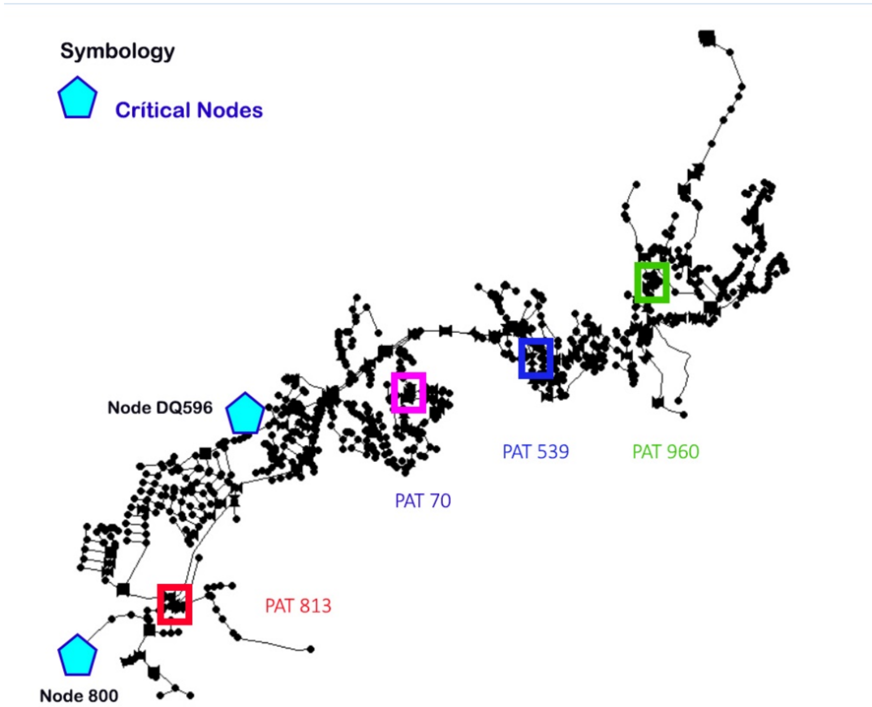

Figure 8. PAT location and critical nodes obtained by the methodology described.

Table 3. Description of pressure on PATs and critical nodes.

Node	Height (masl)	Average Head Pressure (mwc)	Note
DQ245	2017.50	63.31	Upstream PAT960
aux960	2017.50	32.99	Downstream PAT960
QD93	2027.40	41.76	Upstream PAT539
aux539	2027.40	32.99	Downstream PAT539
RDTOT4414	1999.30	62.51	Upstream PAT813
aux813	1999.30	36.00	Downstream PAT813
DQ610	2048.51	38.04	Upstream PAT70
aux70	2048.51	18.45	Downstream PAT70
800	1998.83	62.74	Maximal pressure
DQ596	2068.04	7.99	Minimal pressure

In the initial conditions of the network without PATs, the node DQ596 has a mean pressure of 7.99 mwc. Figure 9 shows the behavior of the pressure at the four proposed PAT locations according to the optimal solution of the algorithm. The large pressure oscillation for the PAT70 is because its location is less affected by some control valves installed by SIMAPAG along the WDN. With this scenario, the node DQ596 maintains its mean pressure and it was the critical node with the same minimum pressure of the network. In these conditions, the OF gives more importance to energy recovery than pressure constraints. This solution is reached over 97 generations with 94,000 individuals generated in a 64 bits system, with 5.22 GB of RAM and a processor i9 with 3.7 GHz, with a simulation period of 124 h and 48 min.

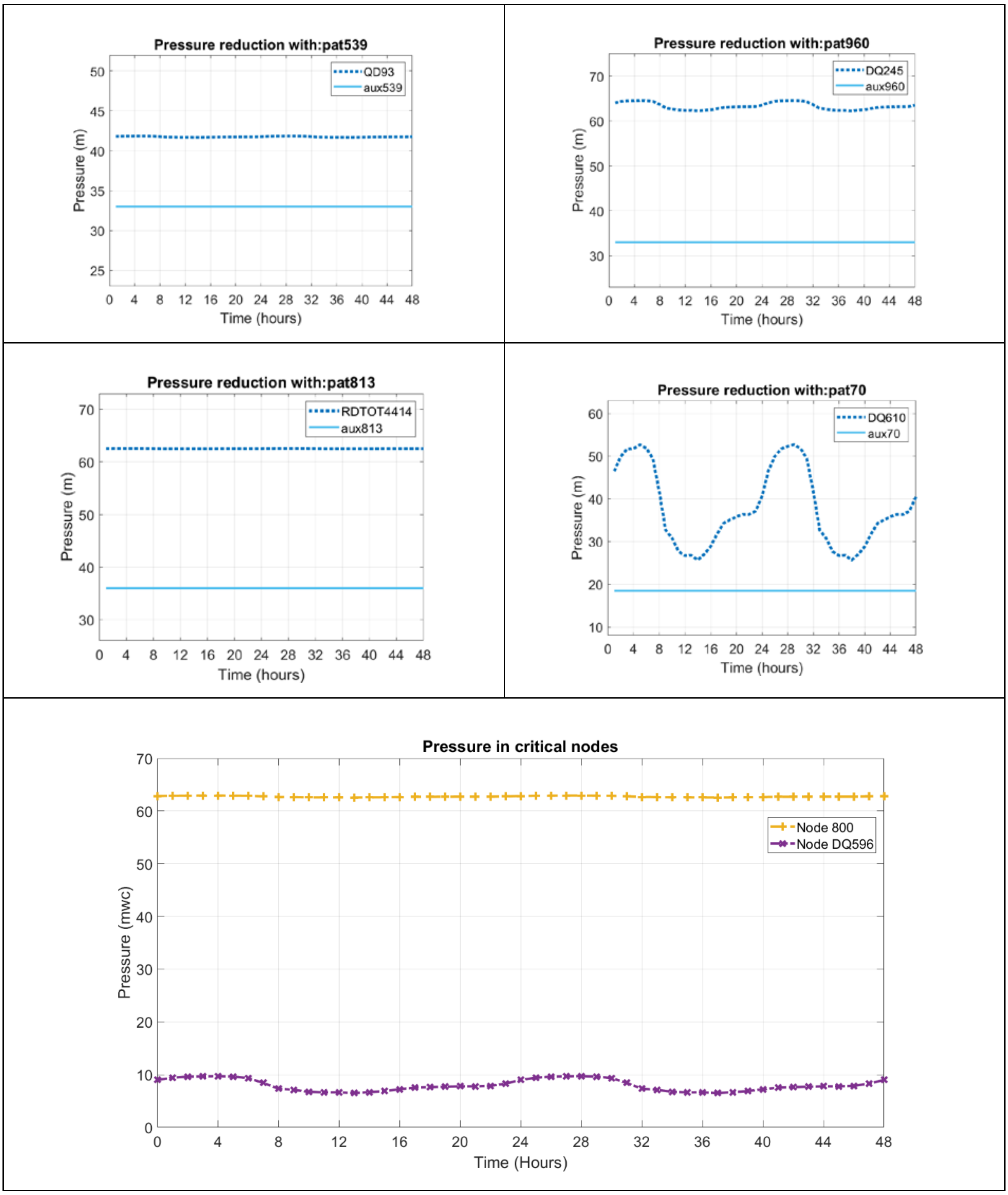

Figure 9. Pressures for PATs and critical nodes in sector 8–12 on extended period.

The data acquired from pressure and flow in the network with the PRV are used to estimate the energy generation assuming a PAT efficiency of 65%. A socio-economic analysis was also performed. Flow through PAT 960 has an average of 0.18 l/s and 30.31 mwc of profitable pressure, which enables it to generate 0.292 kW of power. Flow through PAT 539 has an average of 0.074 l/s and 8.75 mwc of profitable pressure, which enables it to generate 0.035 kW of power. Flow through PAT 813 has an average of 0.58 l/s and 26.51 mwc of profitable pressure, which enables it to generate 0.823 kW of power. Flow through PAT 70 has an average of 2.5 l/s and 19.59 mwc of profitable pressure, which enables it to generate 2.622 kW of power.

After obtaining network data for operation, the calculation of PATs is performed using Equations (3)–(6), which allow us to determine the curves for the PATs. This will allow us to calculate the energy production and socio-economic benefits of the PATs. In cases where PATs are not present in the REDAWN curves, it is considered a scenario where the PAT has 60% efficiency (Table 4).

Table 4. Flow and Head BEP for PATs.

N_{st} (rpm)	N_{sp} (rpm)	Q_{BEPp}(m^3/s)	Q_{BEPt} (m^3/s)	H_{BEPp} (mwc)	H_{BEPt} (mwc)
1540	1450	0.0116	0.0146	9.05	11.54
1500	1450	0.0418	0.0575	13.64	22.72
1450	1450	0.0127	0.0130	32.19	30.73

The PAT is being used to produce electricity for at least 12 h per day, and during this time it is also being used to charge batteries and provide street lighting without consuming electricity from national network. The PAT generates a total of 60 kWh of electricity per day.

Costs are presented in Table 5 and are projected through 15 years; these costs are related to investment cost and maintenance of the equipment. At year zero, it is considered the total inversion of the project.

Table 5. Costs in Present Value ($ USD).

Year	Investment Cost	Maintenance Costs	Street Lighting Maintenance Costs	Total Cost	NPV Cost
0	44,324,772.96	0.00	0.00	44,324,772.96	44,324,772.96
1	0.00	332,435.79	11,708.80	344,144.61	307,271.97
2	0.00	361,357.71	11,898.38	373,256.09	297,557.47
3	0.00	392,795.83	12,091.01	404,886.84	288,190.46
4	0.00	426,969.07	12,286.76	439,255.83	279,155.02
5	0.00	464,115.38	12,485.69	476,601.07	270,436.24
6	0.00	504,493.42	12,687.83	517,181.25	262,020.12
7	0.00	548,384.34	12,893.25	561,277.59	253,893.48
8	0.00	596,093.78	13,101.99	609,195.77	246,043.95
9	0.00	647,953.94	13,314.11	661,268.05	238,459.89
10	0.00	704,325.93	13,529.66	717,855.60	231,130.29
11	0.00	765,602.29	13,748.71	779,351.00	224,044.79
12	0.00	832,209.69	13,971.30	846,180.99	217,193.58
13	0.00	904,611.93	14,197.50	918,809.43	210,567.41
14	0.00	983,313.17	14,427.35	997,740.52	204,157.47
15	0.00	1,068,861.42	14,660.93	1,083,522.35	197,955.48

Notes: Decimals are separated by period (.), and commas (,) to separate thousands.

Leakage cost is calculated from the consumed electricity 0.369 kWh/m^3 by the water loss, which is 45% of the total flow for the network; the estimated leakage is around 42.85 m^3/h, thus, 378 kWh per day are lost by leakage. This consideration is made only with the treatment of water since the system is supplied by gravity and no pumps are required, this cost is absorbed by the WUC since it is a consumed service. Still, by implementing PATs and reducing pressure in system, we can recover 3% of the energy loss by diminishing CO_2 emissions and electric savings.

The benefits are presented in Table 6 at Net Present Value (NPV). It can be observed the sum of them in Figure 10; more than 80% of benefits come from the social aspects derived from street lighting and charging stations, even though PATs energy is sold to national electrical network might not be as highlighted as the socio-economic benefits of street lighting. Auto energy consumption refers to the electrical power that can be sold to the national electric network and discounted from the electric bill, while electric savings refers to the energy generated and consumed by devices not connected to the national electric network.

Table 6. Benefits in Net Present Value ($ USD).

Auto Energy Consumption	CO_2 & Fuel Reduction	Savings In Portage Fee	Reduction on Transit Accidents	Criminality Reduction	Electric Savings	Benefits	NPV Benefits
9918.90	4,040,653.61	8856.03	1,991,978.14	671,446.32	12,351.48	6,735,204.52	6,735,204.52
10,315.70	4,040,725.02	8355.71	1,972,058.36	658,017.39	12,845.54	6,702,317.73	5,984,212.26
10,728.32	4,040,799.30	8689.94	1,952,337.78	644,857.04	13,359.37	6,670,771.75	5,317,898.40
11,157.46	4,040,876.54	9037.54	1,932,814.40	631,959.90	13,893.74	6,639,739.58	4,726,035.48
11,603.76	4,040,956.87	9399.04	1,913,486.26	619,320.70	14,449.49	6,609,216.12	4,200,276.33
12,067.91	4,041,040.42	9775.00	1,894,351.40	606,934.29	15,027.47	6,579,196.48	3,733,212.77
12,550.62	4,041,127.31	10,166.00	1,875,407.88	594,795.60	15,628.57	6,549,675.99	3,318,269.69
13,052.65	4,041,217.67	10,572.64	1,856,653.80	582,899.69	16,253.71	6,520,650.17	2,949,610.99
13,574.75	4,041,311.65	10,995.55	1,838,087.26	571,241.70	16,903.86	6,492,114.78	2,622,056.27
14,117.74	4,041,409.39	11,435.37	1,819,706.39	559,816.86	17,580.01	6,464,065.78	2,331,006.92
14,682.45	4,041,511.04	11,892.79	1,801,509.33	548,620.53	18,283.21	6,436,499.35	2,072,380.53
15,269.75	4,041,616.75	12,368.50	1,783,494.23	537,648.12	19,014.54	6,409,411.90	1,842,552.76
15,880.54	4,041,726.69	12,863.24	1,765,659.29	526,895.15	19,775.12	6,382,800.04	1,638,305.80
16,515.76	4,041,841.03	13,377.77	1,748,002.70	516,357.25	20,566.13	6,356,660.64	1,456,782.56
17,176.39	4,041,959.95	13,912.88	1,730,522.67	506,030.11	21,388.77	6,330,990.77	1,295,446.15
17,863.45	4,042,083.62	14,469.39	1,713,217.45	495,909.50	22,244.33	6,305,787.74	1,152,043.84

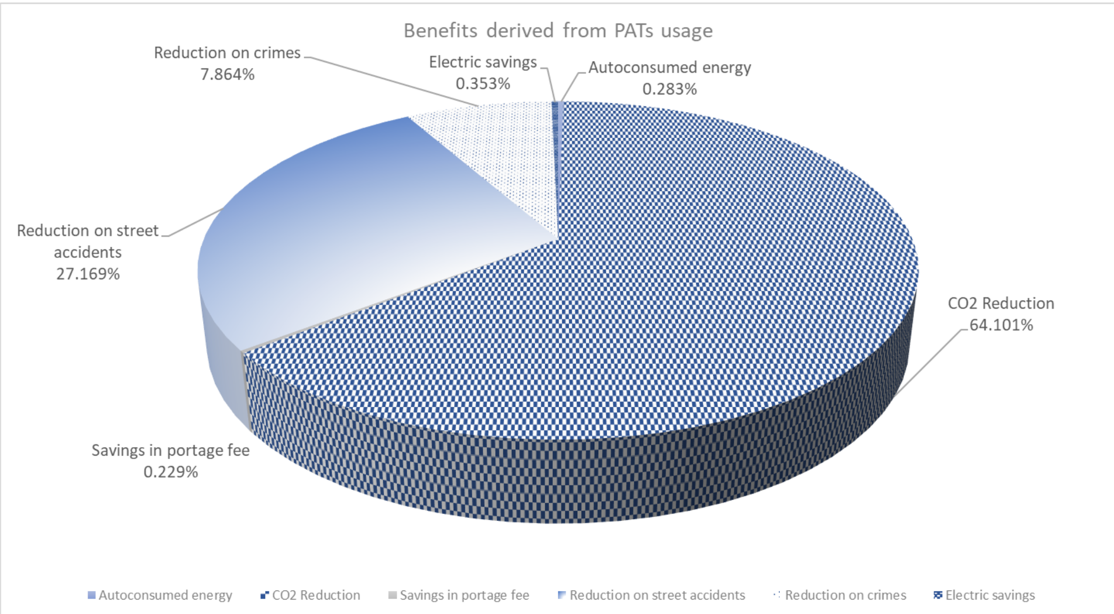

Figure 10. Socio economic benefits with PATs.

Figure 11 shows the payback period. Return of Investment occurs after 12 years considering the installation of four PATs, with one of them providing excess energy to sell to the CFE. The results obtained shows the best ROI of 1.07 reached within multiple configurations made by GAs, this makes the project more profitable in a period of 12 years with a revenue of $166,371.79 USD.

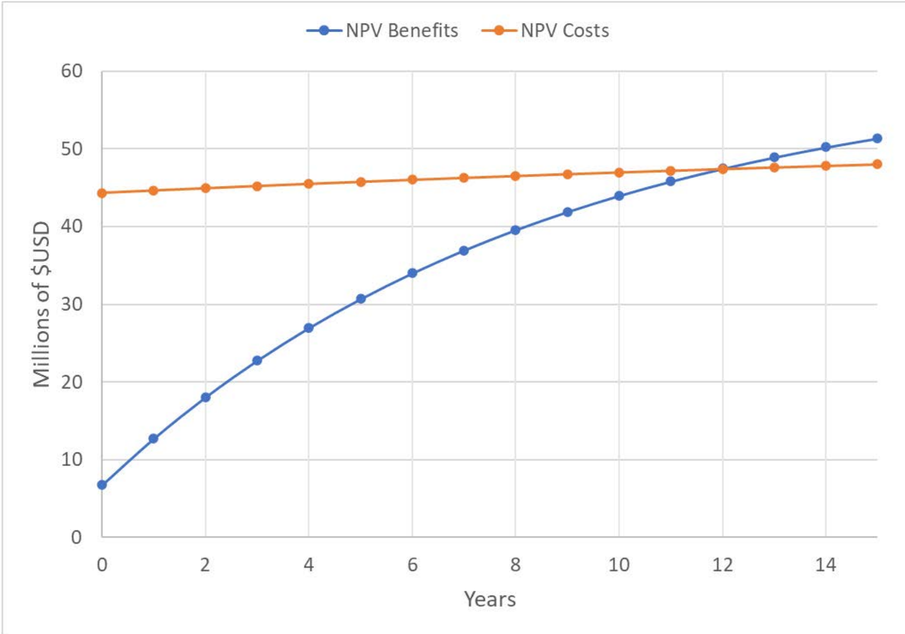

Figure 11. Payback period is represented by the intersection point where NPV benefits overpass NPV costs.

The pressure reduction observed in the network is due to the excess of pressure being absorbed by the PATs to generate energy (Figure 12), even though the reduction is not noticeable in almost all of the network due to the variation of topography, and because the PATs are located in specific zones and not on the main pipe. This is evident at the lower part of the network, as shown on the right of Figure 12, because downstream of PAT 813 the topography increases in some pipelines.

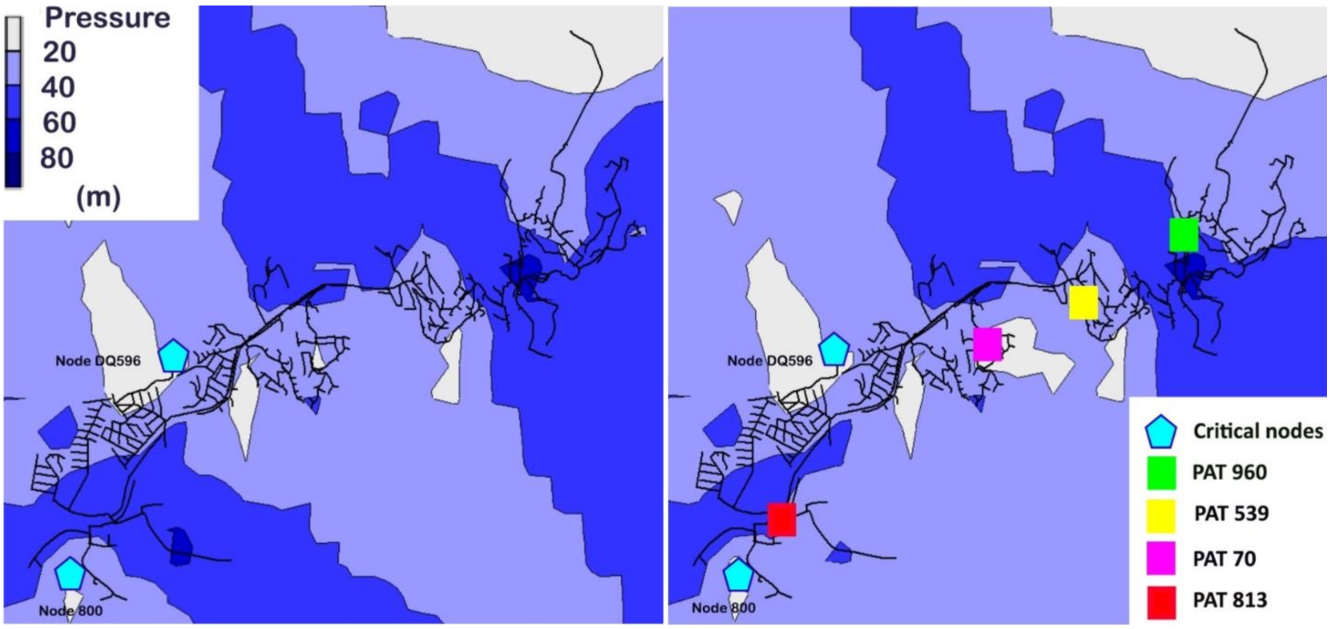

Figure 12. Pressure contour map for network 8–12 statistics maximum from EPANET. Initial network (left contour) and network with PATs (right contour).

4. Discussions and Conclusions

Socio-economic impact highlights the essentiality of building and supporting projects which are off-grid from the electrical network, since selling energy to big industries is not as profitable as expected, representing less than 1% of the economic benefits in this study. Instead, benefits derived from the reduction in CO_2 and fuel consumption represent 64%, and street lighting benefits from the social impact, such criminal and traffic accident reduction, account for nearly 35% of the total benefits contributed by PATs working as DGs for street lighting and charging stations. In this way, distributed generators committed to social life improvements enhance life quality and reduce environmental impact, the excess of energy on electrical networks, and losses for energy transportation. Studies on crime density and car accident density into a GIS model will help future studies to enhance the performance in proposal of distributed generators accompanied with lamps and security equipment.

The research field on PATs in last two years has pointed to three groups: (a) increasing energy production, (b) optimization, and (c) prediction and calculation. In fact, increasing energy production can be within the use of PATs from multiple features, such as reducing water losses, reduction of mechanical friction, etc. In the group of optimizations, the application of different techniques to minimize, maximize and classify to locate the PATs in the network was observed. On the one hand, this study uses GAs as an optimization technique to locate the points where installing this equipment would be more profitable, the GAs proposes four locations in this study, serving a population of 94,000 individuals, and this methodology, which proposes starting with a lower number of PRVs, results in an effective method for diminishing pressure in the network. On the other hand, OF constraints and objectives guarantee a profitable project, this is observed when the ROI is higher than 1; in this study, the ROI is 1.07 with a revenue of $166,371.79 USD surpassing investment and NPV costs after 12 years.

Energy production by itself is not enough for the success of a project; a multidisciplinary perspective must be observed. It is important to consider both financial profitability and long-term environmental and social benefits when evaluating a project. The project described in this paper achieves profitability for four installations of PATs with significant environmental and social benefits over the 15-year design period.

This study highlights the relevance of accompanying PATs as charging stations and security aspects as cameras and street lighting on streets where pressurized pipes cross, specifically in sector 8–12, which is a real network in Guanajuato city, Mexico. The proposed benefits the residents, tourists and students that compose the main population. This study reveals the potential benefits of implementing DGs on similar networks.

The current project aims to reduce pressure in the potable water distribution system by implementing PATs. This translates to a reduction in the number of leaks in the system and, therefore, a decrease in energy losses. Additionally, by reducing the number of leaks, the quality of water in the system is improved by preventing the entry of pathogens into the pipes. These benefits, along with the savings in energy consumption due to the lower volume of treated water and pumping time, were considered in the project as an improvement in energy efficiency. It is important to note that these benefits are not only economic but also environmental and social, as they improve the quality of life for people living around the system and contribute to a more sustainable use of water and energy.

Artificial Intelligence was used in the present methodology to obtain feasible locations for PATs while guaranteeing pressure, flow, and the highest return of investment. The results obtained will improve decision making by WUC involved in the suitability of social, environmental, and water projects.

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J.M.R.; writing—original draft preparation, J.D.P.S.; writing—review and editing, J.M.R., J.A.A.-N., H.M.R., P.A.L.-J., M.P.-S. and J.D.P.S.; visualization, J.D.P.S., J.M.R. and J.A.A.-N.; supervision, J.M.R., J.A.A.-N., H.M.R., X.D.-G., P.A.L.-J. and M.P.-S.; project administration, J.M.R., J.A.A.-N. and H.M.R.; funding acquisition, J.M.R., J.A.A.-N. and H.M.R. All authors have read and agreed to the published version of the manuscript.

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References

1. Chapallaz, J.-M.; Dos Ghali, J.; Eichenberger, P.; Fischer, G. *Manual on Induction Motors Used as Generators*; Springer: Bonn, Germany, 1993; ISBN 978-3-663-14044-3. [CrossRef]
2. Ramos, H.M.; Giralt, L.; López-Jiménez, P.A.; Pérez-Sánchez, M. Water-energy nexus management strategy towards sustainable mobility goal in smart cities. *Urban Water J.* **2021**, 1–12. [CrossRef]
3. Teske, S.; Pregger, T.; Simon, S.; Naegler, T.; Graus, W.; Lins, C. Energy [R]evolution 2010—A sustainable world energy outlook. *Energy Effic.* **2011**, *4*, 409–433. [CrossRef]
4. Elavarasan, R.M.; Pugazhendhi, R.; Irfan, M.; Mihet-Popa, L.; Campana, P.E.; Khan, I.A. A novel Sustainable Development Goal 7 composite index as the paradigm for energy sustainability assessment: A case study from Europe. *Appl. Energy* **2022**, *307*, 118173. [CrossRef]
5. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; General Assembly A/RES/70/1; United Nations: New York, NY, USA, 2015; Available online: https://undocs.org/es/A/RES/70/1 (accessed on 19 April 2022).
6. Avilés, J.; Mayo-Maldonado, J.C.; Micheloud, O. A Hybrid Evolutionary Approach to Design Off-Grid Electrification Projects with Distributed Generation. *Math. Probl. Eng.* **2018**, *2018*, 9135842. [CrossRef]
7. Masuda, H.; Kawakubo, S.; Okitasari, M.; Morita, K. Exploring the role of local governments as intermediaries to facilitate partnerships for the Sustainable Development Goals. *Sustain. Cities Soc.* **2022**, *82*, 103883. [CrossRef]
8. Bonnedahl, K.J.; Heikkurinen, P.; Paavola, J. Strongly sustainable development goals: Overcoming distances constraining responsible action. *Environ. Sci. Policy* **2022**, *129*, 150–158. [CrossRef]
9. Sarkodie, S.A. Winners and losers of energy sustainability—Global assessment of the Sustainable Development Goals. *Sci. Total Environ.* **2022**, *831*, 154945. [CrossRef]
10. Taylor, P.G.; Abdalla, K.; Quadrelli, R.; Vera, I. Better energy indicators for sustainable development. *Nat. Energy* **2017**, *2*, 17117. [CrossRef]
11. Hiruta, Y.; Ishizaki, N.N.; Ashina, S.; Takahashi, K. Regional and temporal variations in the impacts of future climate change on Japanese electricity demand: Simultaneous interactions among multiple factors considered. *Energy Convers. Manag. X* **2022**, *14*, 100172. [CrossRef]
12. Castrejon-Campos, O. Evolution of clean energy technologies in Mexico: A multi-perspective analysis. *Energy Sustain. Dev.* **2022**, *67*, 29–53. [CrossRef]
13. Domínguez, S.J.; de México, E.C. *Análisis de Las Tarifas Eléctricas en Los Sistemas de Agua Potable y Saneamiento de México*; Centro de Estudios Demográficos, Urbanos Y Ambientales: Cd. De México, México, 2019; Available online: https://www.scielo.org.mx/scielo.php?pid=S2448-718X2011000100173&script=sci_arttext (accessed on 1 December 2022).
14. Samora, I.; Manso, P.; Franca, M.J.; Schleiss, A.J.; Ramos, H.M. Energy Recovery Using Micro-Hydropower Technology in Water Supply Systems: The Case Study of the City of Fribourg. *Water* **2016**, *8*, 344. [CrossRef]
15. Jorge, C.; Almeida, M.D.; Covas, D. Energy Balance in Wastewater Systems with Energy Recovery: A Portuguese Case Study. *Infrastructures* **2021**, *6*, 141. [CrossRef]
16. Voltz, T.J.; Grischek, T. Microturbines at Drinking Water Tanks Fed by Gravity Pipelines: A Method and Excel Tool for Maximizing Annual Energy Generation Based on Historical Tank Outflow Data. *Water* **2019**, *11*, 1403. [CrossRef]
17. Williams, A.A.; Smith, N.P.A.; Bird, C.; Howard, M. Pumps as Turbines and Induction Motors as Generators for Energy Recovery in Water Supply Systems. *Water Environ. J.* **1998**, *12*, 175–178. [CrossRef]
18. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Verrilli, F. Real-Time Control of a PRV in Water Distribution Networks for Pressure Regulation: Theoretical Framework and Laboratory Experiments. *J. Water Resour. Plan. Manag.* **2018**, *144*, 04017075. [CrossRef]
19. Carravetta, A.; Del Giudice, G.; Fecarotta, O.; Ramos, H.M. PAT Design Strategy for Energy Recovery in Water Distribution Networks by Electrical Regulation. *Energies* **2013**, *6*, 411–424. [CrossRef]

20. Fontana, N.; Giugni, M.; Glielmo, L.; Marini, G.; Zollo, R. Operation of a Prototype for Real Time Control of Pressure and Hydropower Generation in Water Distribution Networks. *Water Resour. Manag.* **2019**, *33*, 697–712. [CrossRef]
21. Pugliese, F.; Giugni, M. An Operative Framework for the Optimal Selection of Centrifugal Pumps as Turbines (PATs) in Water Distribution Networks (WDNs). *Water* **2022**, *14*, 1785. [CrossRef]
22. Amelio, M.; Barbarelli, S.; Schinello, D. Review of methods used for selecting pumps as turbines (PATs) and predicting their characteristic curves. *Energies* **2020**, *13*(23), 6341. [CrossRef]
23. Algieri, A.; Zema, D.A.; Nicotra, A.; Zimbone, S.M. Potential energy exploitation in collective irrigation systems using pumps as turbines: A case study in Calabria (Southern Italy). *J. Clean. Prod.* **2020**, *257*, 120538. [CrossRef]
24. Barbarelli, S.; Amelio, M.; Florio, G. Experimental activity at test rig validating correlations to select pumps running as turbines in microhydro plants. *Energy Convers. Manag.* **2017**, *149*, 781–797. [CrossRef]
25. Childs, S.M. Convert pumps to turbines and recover HP. *Hydrocarb. Process. Pet. ReJner* **1962**, *41*, 173–174.
26. Derakhshan, S.; Nourbakhsh, A. Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds. *Exp. Therm. Fluid Sci.* **2008**, *32*, 800–807. [CrossRef]
27. Fontanella, S.; Fecarotta, O.; Molino, B.; Cozzolino, L.; Della Morte, R. A Performance Prediction Model for Pumps as Turbines (PATs). *Water* **2020**, *12*, 1175. [CrossRef]
28. Sharma, K.R. *Small Hydroelectric Projects-Use of Centrifugal Pumps as Turbines*; Kirloskar Electric Co.: Bangalore, India, 1985.
29. Yang, S.-S.; Derakhshan, S.; Kong, F.-Y. Theoretical, numerical and experimental prediction of pump as turbine performance. *Renew. Energy* **2012**, *48*, 507–513. [CrossRef]
30. Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Eco-Design Requirements for Water Pump, Commission Regulation (EU) No 547/2012, L165. June 2012. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012R0547 (accessed on 31 August 2022).
31. Koza, J.R. Genetic programming as a means for programming computers by natural selection. *Stat. Comput.* **1994**, *4*, 87–112. [CrossRef]
32. Holland, J. *Adaptation in Natural and Artificial Systems*; University of Michigan Press: Ann Arbor, MI, USA, 1975.
33. Holland, J.H. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*; MIT Press: Cambridge, MA, USA, 1992; Available online: https://mitpress.mit.edu/9780262581110/adaptation-in-natural-and-artificial-systems/ (accessed on 31 August 2022).
34. De Jong, K.A. Analysis of the Behavior of a Class of Genetic Adaptive Systems. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, USA, 1975. Available online: https://deepblue.lib.umich.edu/handle/2027.42/4507 (accessed on 31 August 2022).
35. Kadu, M.S.; Gupta, R.; Bhave, P.R. Optimal Design of Water Networks Using a Modified Genetic Algorithm with Reduction in Search Space. *J. Water Resour. Plan. Manag.* **2008**, *134*, 147–160. [CrossRef]
36. Minaee, R.P.; Mojtaba Afsharnia, A.M.; Ebrahimi, A.A.; Askarishahi, M.; Mokhtari, M. Calibration of water quality model for distribution networks using genetic algorithm, particle swarm optimization, and hybrid methods. *MethodsX* **2019**, *6*, 540–548. [CrossRef]
37. Mohamad Shirajuddin, T.; Muhammad, N.S.; Abdullah, J. Optimization problems in water distribution systems using Non-dominated Sorting Genetic Algorithm II: An overview. *Ain Shams Eng. J.* **2022**, *14*, 101932. [CrossRef]
38. Nicklow, J.; Reed, P.; Savic, D.; Dessalegne, T.; Harrell, L.; Chan-Hilton, A.; Karamouz, M.; Minsker, B.; Ostfeld, A.; Singh, A.; et al. State of the Art for Genetic Algorithms and Beyond in Water Resources Planning and Management. *J. Water Resour. Plan. Manag.* **2010**, *136*, 412–432. [CrossRef]
39. Prasad, T.D.; Nam-Sik, P. Multiobjective Genetic Algorithms for Design of Water Distribution Networks. *J. Water Resour. Plan. Manag.* **2004**, *130*, 73–82. [CrossRef]
40. Sharif, M.N.; Farahat, A.; Haider, H.; Al-Zahrani, M.A.; Rodriguez, M.J.; Sadiq, R. Risk-based framework for optimizing residual chlorine in large water distribution systems. *Environ. Monit. Assess.* **2017**, *189*, 307. [CrossRef]
41. Sharif, M.; Wardlaw, R. Multireservoir Systems Optimization Using Genetic Algorithms: Case Study. *J. Comput. Civ. Eng.* **2000**, *14*, 255–263. [CrossRef]
42. Sharafati, A.; Tafarojnoruz, A.; Shourian, M.; Yaseen, Z.M. Simulation of the depth scouring downstream sluice gate: The validation of newly developed data-intelligent models. *J. Hydro-Environ. Res.* **2020**, *29*, 20–30. [CrossRef]
43. Herrera, F.; Lozano, M.; Verdegay, J.L. Tackling Real-Coded Genetic Algorithms: Operators and Tools for Behavioural Analysis. *Artif. Intell. Rev.* **1998**, *12*, 265–319. [CrossRef]
44. Schaffer, J.D.; Caruana, R.; Eshelman, L.J.; Das, R. A Study of control parameters affecting online performance of genetic algorithms for function optimization. In Proceedings of the 3rd International Conference on Genetic Algorithms, George Mason University, Fairfax, VA, USA, 4–7 June 1989; pp. 51–60.
45. Borkowski, D.; Węgiel, T. Energy-Recovery Pressure-Reducer in District Heating System. *Water* **2018**, *10*, 787. [CrossRef]
46. Fecarotta, O.; McNabola, A. Optimal Location of Pump as Turbines (PATs) in Water Distribution Networks to Recover Energy and Reduce Leakage. *Water Resour. Manag.* **2017**, *31*, 5043–5059. [CrossRef]
47. Nguyen, K.D.; Duc Dai, P.; Quoc Vu, D.; Cuong, B.M.; Tuyen, V.P.; Li, P. A Model for Optimal Localization of Pumps as Turbines in Water Distribution Systems Considering Power Generation Constraints. *Water* **2020**, *12*, 1979. [CrossRef]

48. Demetrios, E.G.; Marios, K.; Stelios, V.; Marios, P.M. EPANET-MATLAB Toolkit: An Open-Source Software for Interfacing EPANET with MATLAB. In Proceedings of the 14th International Conference on Computing and Control for the Water Industry (CCWI), Amsterdam, The Netherlands, 7–9 November 2016.
49. Comisión Estatal del Agua de Guanajuato. *Diagnóstico del Sector Agua Potable y Saneamiento 2019*; Comisión Estatal del Agua de Guanajuato: Guanajuato, México, 2019; Available online: https://sina.conagua.gob.mx/publicaciones/EAM_2019.pdf (accessed on 31 August 2022).
50. García-Ávila, F.; Avilés-Añazco, A.; Ordoñez-Jara, J.; Guanuchi-Que1ada, C.; Flores del Pino, L.; Ramos-Fernández, L. Pressure management for leakage reduction using pressure reducing valves. Case study in an Andean city. *Alex. Eng. J.* **2019**, *58*, 1313–1326. [CrossRef]
51. Ávila, C.A.M.; Sánchez-Romero, F.-J.; López-Jiménez, P.A.; Pérez-Sánchez, M. Optimization tool to improve the management of the leakages and recovered energy in irrigation water systems. *Agric. Water Manag.* **2021**, *258*, 107223. [CrossRef]
52. Ruiz Nápoles, P. Estimación de los costos relativos de las emisiones de gases de efecto invernadero en las ramas de la economía mexicana. *El Trimestre Económico* **2011**, *78*, 173–191. Available online: https://www.eltrimestreeconomico.com.mx/index.php/te/article/view/34 (accessed on 31 August 2022). [CrossRef]
53. Pardo-Bosch, F.; Pujadas, P.; Morton, C.; Cervera, C. Sustainable deployment of an electric vehicle public charging infrastructure network from a city business model perspective. *Sustain. Cities Soc.* **2021**, *71*, 102957. [CrossRef]
54. AEA. *2008 Guidelines to Defra's GHG Conversion Factors: Methodology Paper for Transport Emission Factors. Queen's Printer and Controller of HMSO 2008*; Department for Environment, Food and Rural Af: London, UK, July 2008; Available online: http://www.sthc.co.uk/documents/DERFA_ghg-cf-passenger-transport_2008.pdf (accessed on 1 December 2022).
55. Highway Statistics 2020, 24 September 2022. Available online: https://www.fhwa.dot.gov/policyinformation/statistics/2020/ (accessed on 1 December 2022).
56. EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2019*; United States Environmental Protection Agency: Washington, DC, USA, 2021. Available online: https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf (accessed on 1 December 2022).
57. CFE. Comisión Federal de Electricidad (Tarifas). Available online: https://app.cfe.mx/Aplicaciones/CCFE/Tarifas/TarifasCRENegocio/Tarifas/GranDemandaMTH.aspx (accessed on 1 December 2022).
58. CRE. Cargos por el Servicio de Transmisión para fuentes de energía renovable o cogeneración eficiente por nivel de tensión, a precios de 2018. Comisión Reguladora de Energía. Cd. de México, México. 2020. Available online: https://www.macf.com.mx/wp-content/uploads/2020/06/Resoluci%C3%B3n-893-CRE.pdf (accessed on 6 November 2022).
59. Administración Pública de la Ciudad de México. *Reglamento de Tránsito de la Ciudad de México*; Administración Pública de la Ciudad de México: Centro, México, 2021; pp. 8–130. Available online: https://www.ssc.cdmx.gob.mx/storage/app/media/Transito/Actualizaciones/reglamento-de-transito-cdmx.pdf (accessed on 2 November 2021).
60. SHCP. In *Lineamientos Para la Elaboración y Presentación de los Análisis Costo y Beneficio de los Programas y Proyectos de Inversión*; En Diario Oficial: Cd. de México, México, 2013; Available online: https://www.gob.mx/cms/uploads/attachment/file/21174/Lineamientos_costo_beneficio.pdf (accessed on 1 December 2022).
61. Inflación, Precios al Consumidor (% Anual), Banco Mundial. Available online: https://datos.bancomundial.org/indicator/FP.CPI.TOTL.ZG?view=map (accessed on 19 October 2022).
62. Song, Z.; Feng, S.; Zhang, L.; Hu, Z.; Hu, X.; Yao, R. Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: Real case scenarios. *Appl. Energy* **2019**, *251*, 113411. [CrossRef]
63. IAMSA. Análisis Costo Beneficio de Construcción de Paso a Desnivel Superior Av. Aguascalientes- Av. Las Américas (Tramo de Av. Paseo de la Asunción a Av. Belisario Domínguez), Aguascalientes. November 2019. Available online: https://eservicios2.aguascalientes.gob.mx/servicios/sicaf2/Uploads/16822RendiciondecuentasCostodeProyectosdeInversionObrasPublicasCostodePrincipalesProyectosBelisarioDominguezAguascalientesANIO2019.pdf (accessed on 2 November 2021).
64. Lawson, T.; Rogerson, R.; Barnacle, M. A comparison between the cost effectiveness of CCTV and improved street lighting as a means of crime reduction. *Comput. Environ. Urban Syst.* **2018**, *68*, 17–25. [CrossRef]
65. Painter, K.A.; Farrington, D.P. The financial benefits of improved street lighting, based on crime reduction. *Light. Res. Technol.* **2001**, *33*, 3–10. [CrossRef]
66. INEGI. *Encuesta Nacional de Seguridad Pública Urbana*; Tercer Trimestre; INEGI: Guanajuato, México, 2021; Available online: https://www.inegi.org.mx/contenidos/programas/ensu/doc/ensu2021_septiembre_presentacion_ejecutiva.pdf (accessed on 19 October 2021).
67. Dirección General de Obra Pública. *Catálogo General de Precios Unitarios de Obras Públicas en León*; Dirección General de Obra Pública: León, México, 2021; Available online: https://apps.leon.gob.mx/obrapublica/index.php?option=com_docman&Itemid=81 (accessed on 8 November 2021).
68. Manzano, E.R. Beneficios del uso del alumbrado público, la reducción de la tasa de accidentes nocturnos. *Asoc. Argent. De Luminotecnia* **2007**, *84*, 38–46.
69. World Bank Inflación. Índice de Deflación del PIB (% Anual)-Argentina. *Banco de Datos.* **2021**. Available online: https://datos.bancomundial.org/indicator/NY.GDP.DEFL.KD.ZG?locations=AR (accessed on 16 September 2022).

70. Cuevas Colunga, A.C.; Silva Rivera, M.E.; Cadengo Ramirez, M.; Villegas Villegas, N.; Mendoza Diaz, A. *Estadística de Accidentes de Tránsito, Año 2019*; Instituto Mexicano del Transporte: Santiago de Querétaro, México, 2019. Available online: https://www.sct.gob.mx/fileadmin/DireccionesGrales/DGST/Estadistica_de_accidentes/A%C3%B1o_2019/dt82.pdf (accessed on 26 October 2021).
71. INEGI. *Accidentes de Tránsito Terrestre en Zonas Urbanas y Suburbanas por Clase por Entidad y por Año*; INEGI: Guanajuato, México, 2020. Available online: https://www.inegi.org.mx/app/tabulados/interactivos/?px=ATUS_1&bd=ATUS&idrt=168&opc=t (accessed on 12 November 2021).
72. The World Bank. *Violence in the City Understanding and Supporting Community Responses to Urban Violence*; The World Bank: Washington, DC, USA, 2011. Available online: https://openknowledge.worldbank.org/bitstream/handle/10986/27454/638880WP0Viole00BOX361532B00public0.pdf?sequence=1&isAllowed=y (accessed on 19 October 2021).
73. Atkinson, G.; Healey, A.; Mourato, S. Valuing the costs of violent crime: A stated preference approach. *Oxf. Econ. Pap.* **2005**, *57*, 559–585. [CrossRef]
74. McCollister, K.E.; French, M.T.; Fang, H. The cost of crime to society: New crime-specific estimates for policy and program evaluation. *Drug Alcohol Depend.* **2010**, *108*, 98–109. [CrossRef]
75. INEGI. *Incidencia Delictiva*; INEGI: Guanajuato, México, 2019. Available online: https://www.inegi.org.mx/temas/incidencia/ (accessed on 9 November 2018).
76. INEGI. Densidad de Población por Entidad Federativa, 1990 a 2020. 2020. Available online: https://www.inegi.org.mx/app/tabulados/interactivos/?pxq=Poblacion_Poblacion_07_fb7d5132-39f0-4a6c-b6f6-4cbe440e048d (accessed on 1 December 2022).
77. INEGI. *Tasa de Crecimiento Media Anual de la Población por Entidad Federativa, Años Censales de 2000, 2010 y 2020*; INEGI: Guanajuato, México, 2020. Available online: https://www.inegi.org.mx/app/tabulados/interactivos/?pxq=Poblacion_Poblacion_03_13b8bdfc-8744-4623-a652-03cb6901fd47&idrt=123&opc=t (accessed on 9 November 2021).
78. Stefanizzi, M.; Capurso, T.; Balacco, G.; Binetti, M.; Camporeale, S.M.; Torresi, M. Selection, control and techno-economic feasibility of Pumps as Turbines in Water Distribution Networks. *Renew. Energy* **2020**, *162*, 1292–1306. [CrossRef]
79. Pineda Sandoval, J.D.; Brentan, B.M.; Lima, G.M.; Cervantes, D.H.; García Cervantes, D.A.; Ramos, H.M.; Delgado Galván, X.; Mora Rodríguez, J.d.J. Optimal Placement and Operation of Chlorine Booster Stations: A Multi-Level Optimization Approach. *Energies* **2021**, *14*, 5806. [CrossRef]