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Optimal energy harvesting plans in water distribution networks considering the stakeholders' utilities

Milad Latifi [a,*], Ramiz Beig Zali [a], Reza Kerachian [b]

[a] Centre for Water Systems, University of Exeter, UK
[b] School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

This paper delves into identifying the optimal scenario for the implementation of micro-turbines, specifically Pump-*as*-Turbines (PaTs), in a water distribution network (WDN) by achieving the highest consensus among the involved stakeholders. Utilising a simulations-optimisation model, the best location, type, and operation hours for micro-turbines were selected within a case study WDN. The objective was to maximise the generated energy, while maintaining the standard hydraulic conditions of the WDN. A total of 84 scenarios were developed, considering the number of installed turbines, allocation of the generated energy, and pricing schemes. The scenarios explore the possibilities of allocating the generated electricity to the water company, national grid, cryptocurrency mining, or electric car charging. Evaluation of the scenarios involves 36 criteria, and the study identifies 18 stakeholders involved in water and energy management within the case study. Stakeholder utility with respect to the criteria was determined through interviews, and weights for each stakeholder were assigned based on previous studies. The utility of each scenario was computed in a matrix, and scenarios were ranked accordingly, revealing that the scenario involving the generation of electricity by five turbines sold to the grid at twice the current price garnered the highest stakeholder support.

1. Introduction

Nowadays, water distribution networks (WDNs) play an essential role in supplying safe and sufficient drinking water for human communities. These systems are designed to deliver the demanded water in a standard range of pressure. Pressure management programs are implemented to maintain the pressure within this specified range [1–3]. Excess pressure in a WDN is commonly dissipated by installing pressure-reducing valves (PRVs). In recent years, micro hydropower devices have been utilised to both reduce the hydraulic pressure and generate electrical energy from water flowing in the pipes [4–7].

Hydropower is a renewable energy source, making it an attractive and profitable option for sustainable energy. In certain nations, hydroelectric power serves as the primary source of electricity production, such as Norway at 98 %, Brazil at 84 %, Switzerland at 82 %, and Sweden at 77 % [8]. Globally, hydropower contributes to 41 % of the total renewable energy supply [9]. Hydropower systems situated in rivers benefit from a relatively constant flow, ensuring a consistent and reliable energy source. The longevity of hydropower infrastructure enhances its profitability, as well-designed hydroelectric plants can operate for several decades with minimal maintenance costs.

The scalability of hydropower installations, ranging from small-scale run-of-river systems to large reservoir-based dams, provides flexibility in meeting diverse energy needs. Micro hydropower plants, particularly in remote areas, offer decentralised energy solutions with lower environmental impact and construction costs compared to larger hydro projects, contributing to sustainable development (Binama et al., 2017; [10]). Despite their lower production capacity, micro hydropower can assist the national grid in overcoming peak demand during high-consumption days. Consequently, governments incentivise the purchase of power generated by these plants to reduce the necessity for expanding power plant capacity.

Despite their advantages, micro-turbines may not be universally applicable. From a technical standpoint, high-pressure WDNs provide a suitable environment for the installation of micro-turbines, in which their excessive pressure can be consumed in micro-turbines to generate electricity [11–14]. However, from an economic perspective, implementing micro-turbines requires investment which should be returned within a reasonable timeframe. Consequently, a techno-economic feasibility analysis becomes essential before deciding on the

* Corresponding author. Harrison Building, Streatham Campus, University of Exeter, North Park Road, Exeter, UK, EX4 4QF.
E-mail addresses: m.latifi@exeter.ac.uk (M. Latifi), rb815@exeter.ac.uk (R. Beig Zali), kerachian@ut.ac.ir (R. Kerachian).

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integration of micro-turbines into a WDN [15–17]. Moreover, the number, type, and location of micro-turbines in a WDN could be selected in a way to optimise the generated energy [18–22], surplus pressure in the network [23], economic profits ([24]; Morani et al., 2021; [25]), and water saving [26], among other considerations. Various optimisation algorithms were employed to optimise the objectives in energy harvesting projects in a WDN, including Genetic Algorithm [18,27], Non-dominated Sorting Genetic Algorithm (NSGA-II) [28], Harmony Search Algorithm [29]; Simulated Annealing [30], Strength Pareto Evolutionary Algorithm 2 [24]; Particle Swarm Optimisation [31], among the others. In this study, a NSGA-II was utilised to maximise energy production through PaTs.

Micro hydro-turbines involve the utilisation of intricate and advanced technologies during the manufacturing process. However, pump-*as*-turbines (PaTs) benefit from the conventional pumps in reverse. Essentially, while conventional pumps use electricity to rotate the shaft and flow water through pipes, PaTs generate electricity by allowing water to drive the propellers and shaft [32]. The adaptability of pump devices and their cost-effectiveness makes them suitable for modification to function in reverse [33]. However, the primary challenges associated with PaTs lie in their inability to regulate flow, as they lack components for flow control. Consequently, their performance experiences a notable decline in off-design and overflow operating conditions (Binama et al., 2017). Another issue pertains to the availability of characteristic curves for PaTs, given that many pump manufacturers do not furnish these curves for reverse conditions [34,35]. Nevertheless, various studies have established relationships between the pump and PaT characteristic curves [36,37]. When these curves are accurately available, PaTs emerge as viable tools for electricity generation in water distribution networks (WDNs). However, infrequent deployment of PaTs in WDNs could stem from social and political factors, including: 1) limited awareness among water utility managers about the energy recovery potential of this technology; 2) concerns regarding its safety and reliability, posing potential management challenges; 3) complex interactions with other stakeholders; and 4) inadequate incentives or lack thereof to encourage water utility managers to adopt these devices [33].

Implementing micro hydropower plants in a WDN involves several stakeholders, each having different interests, powers, satisfaction, and access to information [38]. Each stakeholder has their utilities in the scenarios for applying the micro-turbines in the WDN, either advancing certain scenarios or opposing the execution of others. Stakeholder analysis (SA) proves instrumental in comprehending the unique attributes of each participant in a project. Social network analysis (SNA) delves into the collaborative and non-cooperative interactions among stakeholders. It unveils the dynamics of how each stakeholder functions within their network, influencing and being influenced by others. The importance of the stakeholders in a social network can be quantified by centrality metrics, e.g., in-degree, out-degree, between-ness, and beta centralities ([39]; [40]). The outcomes of these analyses provide decision-makers with valuable insights, facilitating the identification of scenarios that encounter minimal resistance and garner the highest consensus among stakeholders. The majority of existing literature has predominantly concentrated on identifying optimal techno-economic scenarios for the installation of micro-turbines [41–45]. Ikäheimo & Koreneff [46] studied the stakeholders involved in the deployment of microgenerators, with a focus on micro - Combined Heat and Power (μ-CHP) plants. Using micro-turbines in WDNs was not among the options they explored. Urošević & Marinović [47] employed PROMETHEE and Analytic Hierarchy Process methods for multi-criteria decision--making in ranking the small hydropower plant projects in dams. In this process, they asked the stakeholders about their preferences to weigh the criteria, while none of the plants were supposed to be installed in a WDN. Few works inclusively looked at investigating the best scenario for installing micro hydropower plants in a WDN from stakeholders' perspective. Latifi et al. [20] explored of various configurations involving the installation of PaTs in a WDN case study in Tehran, Iran, where excess pressure and the potential for micro-turbine installation existed. Their study aimed to identify the optimal location, type, and operating hours for each available PaT to maximise the overall energy output. In subsequent work, Latifi et al. [38] acknowledged the stakeholders involved in the aforementioned case study, employing both SA and SNA to comprehend individual stakeholder characteristics and their interrelationships.

The present research explores different scenarios for PaT implementation in a WDN and investigates the criteria concerning acceptance or rejection of the scenario, for each stakeholder. Employing a novel approach, this paper ranks the scenarios regarding the mentioned criteria and based on the importance of each stakeholder in the social network. This method facilitates decision-makers in identifying scenarios that enjoy the highest consensus among stakeholders.

2. Case study

The case study WDN in this research is in Tehran, Iran, a city located at steep foothills of Alborz Mountains. The WDN is fed by Reservoir No. 23, which, in simplified form, has 46 pipes, 55 nodes, and 5 pressure zones (Fig. 1). The details of the WDN are provided in Latifi et al. [20]. Given the presence of excess pressure within the network, there exists potential for the installation of PaTs to harness electricity from water flowing in the pipes. Four types of PaTs with various specific speeds were considered for this purpose. Fig. 2 presents the specifications of the turbines considered in the case study through a Hill diagram. The turbines have the flexibility to be installed on any pipe within the network in a parallel configuration. This allows for the water to either flow through the PaT (active PaT) or bypass it (inactive PaT). In a previous study [20], a hydraulic simulation model was integrated with an optimisation model to identify optimal locations, types, and operation regimes for different numbers of PaTs. The goal was to minimise the operational costs of a pumping station. Essentially, the PaTs were integrated with the pumping station to contribute a portion of its required

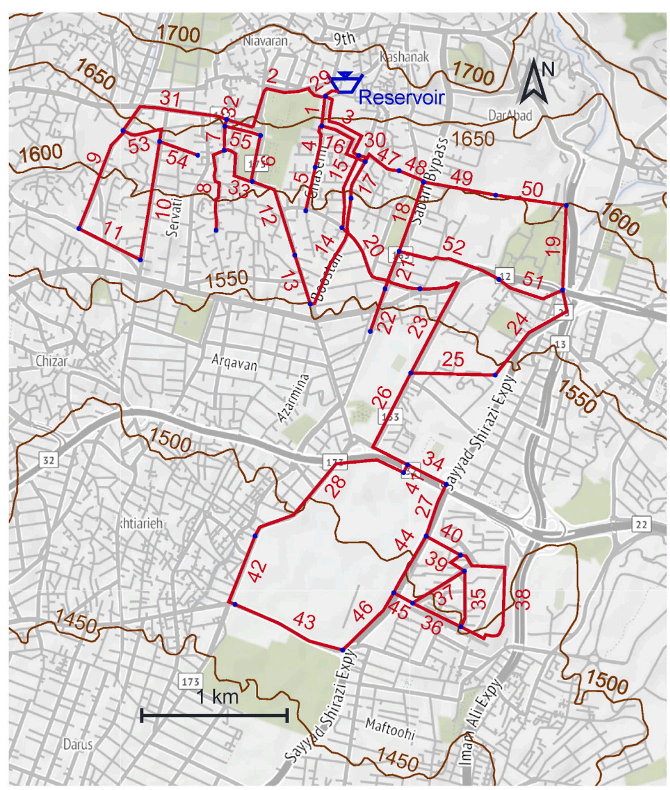

Fig. 1. Map of the case study WDN in this research. [20].

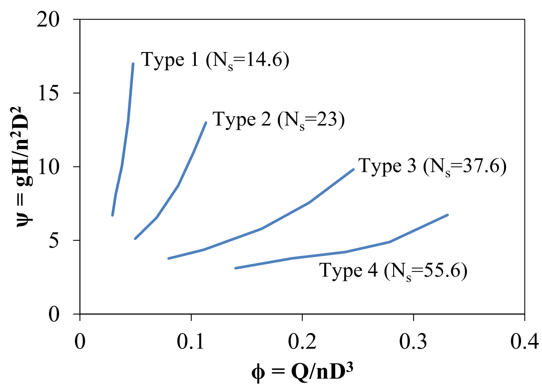

Fig. 2. Hill diagram for the PaTs used in this study. ψ and φ are dimensionless head number and dimensionless flow rate number, respectively. *Ns* is specific speed; *H* is pressure head; *Q* is flow rate; *D* is impeller diameter; and n is rotational speed.
(Data from Derakhshan and Nourbakhsh, 2008).

energy. The operational hours of PaTs were selected to maximise the supply of the pump station, while sustaining the standard performance of the WDN. They found out that this case study has the potential for installing a maximum of 5 PaTs and adding more PaTs is not affordable, i.e., the cost of installing new PaTs does not recover through the sales of the generated electricity in them. This research revisits the same case study, introducing a new objective function. The characteristics of the PaTs are detailed in reference mentioned above.

Latifi et al. [38] studied the stakeholders in the case study above and the relationship between stakeholders. They identified 18 stakeholders in national, regional, and local levels. Interviews were conducted with water experts and representatives from each stakeholder to understand their roles and influence in water and energy management within the WDN. Stakeholder analysis (SA) was carried out to explore the power, interest, satisfaction, and access to information of each stakeholder. These concepts were quantified in a Likert scale [48] ranging from 1 to 5. The key stakeholders with the highest power and interest included the Water and Wastewater Company (*WWC*), Regional Water Board Company (*RWBC*), Regional Electricity Company (*REC*), and Ministry of Energy (*MoE*), which make policies about energy management in a WDN. These entities formulate policies related to energy management in WDNs and exhibit a keen interest in investing in renewable energy, thereby facilitating the installation of micro hydropower plants. Although consumers (*Cnsm*) have high interest in the network, their power to influence on management of the system is low. Banks and Financial Institutions (*BFI*), despite their pivotal role in financing micro-turbines, demonstrated low power, interest, and access to information in the WDN, diminishing their effectiveness in new projects. In

Table 1
Characteristics of the stakeholders in the case study [38].

Group	Stakeholder Name	Abbreviation	Role in energy management in a WDN	Power[a]	Interest[b]	Beta centrality[c]	Normal weight
National	Planning & Budget Org.	P&B	Formulating national policies and allocating budgets for urban infrastructure projects	4.18	2.04	28,369.89	1.28
	Parliament	Parl	Developing and implementing supportive acts to encourage investment in renewable energies (e.g., tax exemptions, etc.)	3.82	1.88	25,801.39	1.07
	Ministry of Energy	MoE	Establishing operational regulations for WDNs, managing water resources allocation, overseeing electricity production in power plants, and setting energy tariffs	4.23	2.4	33,694.46	1.62
Regional	Water & Wastewater Company	WWC	Designing, constructing, and operating the facilities for supplying, treatment, transmitting, and distributing of drinking water, as well as implementing plans for electricity generation in WDNs	4.27	4.2	38,355.87	2.36
	Regional Water Board Company	RWBC	Protecting the quality and quantity of water resources, water supply, and transmission for WWC, adhering to the MoE water allocation policies	3.09	3.64	28,484.12	1.39
	Regional Electricity Company	REC	Providing necessary energy for water system facilities and purchasing hydropower at supportive prices	3	2.82	20,442.64	0.86
	Environment Protection Agency	EPA	Monitoring the environmental impacts of infrastructure projects, promoting renewable energy generation, and supporting pollution mitigation initiatives	2.36	2.45	25,502.48	0.89
	Health Organisation	HO	Conducting water quality control in WDNs	1.91	1.73	10,860.97	0.29
	Banks/Financial Institutions	BFI	Investing in and funding profitable projects, including renewable energy projects	2.18	1.45	25,370.22	0.67
Local	Governance	Gov	Implementing government policies at the local level	2.27	2.64	16,972.79	0.61
	City Council	CC	Policy-making for urban management through appointing the mayors and supervising the municipalities, intervention in WDNs' operation as a shareholder in water companies	3.18	3.18	33,527.24	1.55
	Municipality	Mun	Facilitating the construction and operation processes of WDN projects, with sub-organisations: Firefighting and Landscape	3.09	2.91	31,846.98	1.39
	Firefighting Organisation	FO	Serving as consumers of water for firefighting purposes	1.55	1.64	17,010.37	0.39
	Landscape	Lan	Acting as consumers of water in urban landscapes	1.82	1.82	14,638.81	0.39
	Contractors	Cntr	Executing infrastructure projects (e.g. construction, procurements, and installing the small hydropower generators)	2.36	2.64	23,855.26	0.87
	Consultants	Cnsl	Conducting technical studies, detailed design, and supervising infrastructure projects (e.g. designing small hydropower generators)	2.36	2.55	23,779.33	0.85
	NGOs	NGO	Exercising public supervision on the quality of WDN services, advocating for reduced water prices, and facilitating communication between the public and authorities	2	2.09	24,062.08	0.72
	Consumers	Cnsm	Representing the main customers of WDNs, with direct/indirect supervision by the government, parliament, and city council through voting in the election	1.8	4.3	18,182.40	0.81

[a] Power: The ability of stakeholders to impact the energy management and energy harvesting projects in WDN.
[b] Interest: The degree to which the energy management and energy harvesting projects in WDN have an impact on the institutional interests of the stakeholders.
[c] Beta centrality: a measure of importance of the stakeholder in the social network.

the social network analysis (SNA) of stakeholders, the cooperative and non-cooperative relationships between stakeholders were studied. In-degree, out-degree, between-ness, and beta centralities [39] were utilised to quantify the influence of each stakeholder in the social network. Table 1 presents the stakeholders, their roles, powers, interests, and beta centrality, which will be used in this study.

3. Methodology

This paper looks at different scenarios for generating electricity in WDNs using micro-turbines, specifically PaTs. Traditionally, selecting the optimal scenario in such projects relies on techno-economic analysis, considering technical aspects such as maximising generated energy, maintaining standard hydraulics in the WDN, and the availability of facilities. Economic analysis factors in the required investment budget, return on investment period, total project revenue, and more to identify the most favourable scenario. However, as highlighted earlier, energy harvesting projects in WDNs involve multiple stakeholders with diverse interests, each expressing preferences for certain aspects of the project. From this perspective, each stakeholder is interested in specific scenarios, and is able to push those scenarios forward. In this context, if decision-makers fail to recognise the stakeholders, along with their powers and interests, they may choose scenarios lacking sufficient support from influential stakeholders. In contrary, if the implementing scenario is selected with consensus of the stakeholders, it has a higher chance of success. This paper deals with a novel approach to select the best scenario for implementing micro-turbines in a WDN, ensuring it has the highest support from stakeholders.

3.1. Simulation-optimisation model

As previously noted, the maximum number of economically feasible PaTs in the examined WDN is limited to five. To customise the scenarios, six states were considered, representing the utilisation of 0–5 PaTs. In this context, 0 signifies the absence of PaTs, allowing the network to operate in its usual manner without any associated investment or energy generation. In the scenario involving the installation of 1–5 PaTs, the locations, types, and operational hours for each PaT were determined through an optimisation model:

$$\begin{aligned} &Max \quad E=\sum_{i=1}^{NT}\sum_{t=1}^{T}P_{i,t}\cdot\Delta t \\ &\text{subject to}: h_j\geq h_{\min} \quad j=1,\ldots,NN \\ &Var=[Type_{1-4}, Location_{1-46}, Time_{1-8}] \end{aligned} \tag{1}$$

where, E is the total electricity generated by the turbines; NT is the number of turbines installed in the network; T is the number of simulation time steps; $P_{i,t}$ is the power of electricity generation by i-th turbine in t-th time step; Δt is the time steps duration; h_j is the pressure in j-th node; and $h_{\min}$ is the minimum allowable pressure in the network with NN nodes and was considered equal to 18 m $Type_{1-4}$ indicates the PaT type which can be selected among four available models; $Location_{1-46}$ is the pipe number for PaT installation; and $Time_{1-8}$ is the PaT operating hours, i.e., eight 3-hr time steps.

The optimisation was conducted using the NSGA-II algorithm [49] implemented in MATLAB software. A population size of 100 was selected for the genetic algorithm. The optimiser was configured to produce integer decision variables within specified boundaries for the type, location, and operation time of the PaTs. A mutation factor of 0.01 was employed to mitigate the risk of results becoming trapped in local optima. The optimisation process ran for either 1000 generations or until the results repeated for 20 generations, whichever came first. Optimisation was repeated at least five times and the best results were taken as the optimal solution.

By integrating the optimisation model mentioned above with the hydraulic model of the WDN, the system identifies the optimal locations, types, and operational schedules for PaTs to maximise the generated energy. The outcomes of this optimisation model are summarised in Table 2.

3.2. Scenarios

While the energy output from the turbines may not be substantial, its diverse applications are noteworthy. In this case study, four specific applications were identified for allocating renewable energy, including internal usage within water and wastewater facilities, integration into the power grid, mining cryptocurrency, and charging e-cars. Each application is elaborated upon in the subsequent sections.

1) Internal consumption in water and wastewater facilities: In this case, *WWC* can collect all produced energy and use it in various facilities, including pumping stations, water/wastewater treatment plants, and more. Additionally, minimal communication with other stakeholders is required, rendering this option easy to implement from a perspective of mitigating conflicts among stakeholders.
2) Integration into the national electricity grid: By transferring the generated energy to the national electricity grid, it can be employed to smooth out electricity consumption peaks during high-demand periods. Within WDNs where there is ample excessive pressure, energy recovery can be implemented even during periods of peak energy demand. The connection of small generators to the grid allows it to meet all demands on a few high-demand days, obviating the need for the government to invest in constructing new power plants to expand electricity generation capacity. As a result, the government endorses small generators by purchasing their generated energy at incentivised prices.
3) Cryptocurrency mining: The energy can be used for cryptocurrency mining, an emerging sector with high electricity demand that is restricted or prohibited in some countries due to its environmental

Table 2
The best configuration for installing 0–5 PaTs in the case study WDN.

Number of turbines	Turbine location (Pipe number)	Turbine types	Turbine working times	Turbine procurement cost ($)
0	[–]	[–]	[–]	0.0
1	[9]	[1]	[1 0 1 0 1 1 1 1]	4752.0
2	[9, 11]	[1, 2]	[0 1 1 1 1 1 1 1] [1 1 1 1 1 1 0 1]	11800.8
3	[9, 7, 11]	[1, 2, 2]	[1 1 1 1 1 1 1 1] [1 1 0 0 0 1 0 1] [1 1 1 1 1 0 1 1]	18849.6
4	[9, 7, 11, 23]	[1, 3, 2, 3]	[1 1 1 1 1 1 1 1] [0 1 0 0 1 0 1 1] [0 1 1 1 0 0 0 1] [1 0 0 0 1 0 1 0]	30852
5	[9, 7, 11, 23, 24]	[1, 2, 4, 3, 2]	[1 1 1 1 1 1 1 1] [0 1 1 1 1 1 0 1] [0 1 0 0 1 0 0 0] [1 0 0 1 1 0 1 1] [0 1 1 0 0 1 0 1]	39715.2

impact. Recent concerns about its carbon and water footprint have escalated [50–52]. The renewable nature of the electricity generated by PaTs makes it suitable for cryptocurrency mining without imposing strain on the national grid, utilising government subsidies, or contributing to carbon footprint concerns. Additionally, the appreciation in the value of these currencies contributes to enhanced revenue from micro-turbines. Bitcoin is selected in this research to represent cryptocurrencies.

4) Electric vehicle charging: Utilising the renewable energy generated by micro-turbines to charge electric vehicles is considered a mutually beneficial situation. As electric cars contribute to reducing carbon footprint and dependence on fossil fuels, employing renewable energy aligns with environmental goals [53–55]. E-car charging stands can be built within the city, near the PaT installations, reducing the requirement for long-distance power transmission.

Incorporating the pricing of the generated energy is another crucial aspect in the design of scenarios. As a renewable energy source, electricity generated in micro-turbines typically receives government support in many countries. On the other hand, de-peaking impact of these small generators persuades the government to acquire the generated energy at incentivised prices. In the case study, national grid purchases the electricity at a rate of 0.03 $/kWh. To evaluate the scenarios' sensitivity to energy prices, four different prices, 0.015, 0.03, 0.06, and 0.12 $/kWh, were considered for the sale of the electricity to WWC and REC. While higher prices may attract investors to finance energy harvesting plans, such scenarios tend to receive less support from the government.

Over time, the energy requirement for mining a new Bitcoin has been increasing. Concurrently, the value of mined Bitcoins tends to rise, emphasising the enduring significance of Bitcoin mining. Presently, the energy needed to mine a Bitcoin is approximately 266,000 kWh [56]. Moreover, the minimum, mean, and maximum Bitcoin prices over a three-year period ending in 2023, were recorded as 15,787, 34,771, and 67,566 $, respectively (Fig. 3). Considering expenses associated with mining beyond electricity, it was assumed that the energy could be sold to miners at 50 % of the Bitcoin value. By dividing the Bitcoin price by the energy requirement for each Bitcoin and factoring in a 50 % reduction, three energy prices, corresponding to the minimum, mean, and maximum price of Bitcoin over the three-year period (2021–2023) were considered as 0.03, 0.06, and 0.12 $/kWh.

The utilisation of renewable energy was also contemplated for charging electric cars. In this context, the standard charging price was set at 0.04 $/kWh. To perform sensitivity analysis and acknowledge the impact of using this energy for another environmentally friendly purpose, a discounted rate of 0.02 $/kWh was considered to incentivise electric car owners. Furthermore, a higher rate of 0.08 $/kWh was taken into account to stimulate investor participation in these projects.

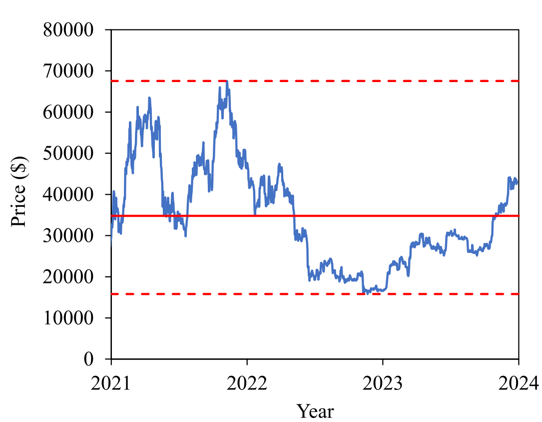

Fig. 3. Bitcoin price in the period 2021–2023.

Assigning names to the scenarios involved assigning a unique three-digit number to each state. Table 3 provides a summary of the scenarios and their corresponding states. For instance, scenario 201 signifies the utilisation of one turbine in the WDN and selling the generated electricity to REC for 0.015 $/kWh. As a result, 84 scenarios were formulated, varying in the number of turbines, energy allocations, and pricing.

3.3. Scenario selection approach

This paper undertakes scenario selection based on the preferences and interests of stakeholders involved in WDN. To gain insight into stakeholders' perspectives on the scenarios, a two-phase interview was carried out with stakeholder representatives. Each phase involved the participation of at least two delegates from each stakeholder group, along with academic scholars forming an experts' panel. The number of experts providing comprehensive answers varied among stakeholders; nonetheless, more than two delegates expressed the views of consumers. In the initial phase, a set of criteria was established to evaluate the scenarios, encompassing 36 criteria aimed at assessing the preferences of each stakeholder in participating in energy harvesting projects within WDNs. Each criterion was put forth by one or more stakeholders during expert interviews. For instance, the criterion 'satisfaction of household costumers with the quantity and quality of drinking water' (criterion 3 in Table 4) holds significance for *WWC*, *MoE*, and *RWBC*. Notably, 'increase in return-on-investment rate and acceleration of investment return in water industry' (criteria 25 and 26) were crucial for Banks and Financial Institutions (*BFI*) in supporting a scenario. As another example, 'less complexity in design and implementation' (criteria 28 and 29) were suggested by Consultants (*Cnsl*) and contractors (*Cntr*), respectively. Table 4 provides an overview of all criteria considered in this study to evaluate the scenarios.

In the second part of the interview, the interviewees determined the

Table 3
Summary of scenarios in the present study.

Energy allocation	Third decimal place in scenario number	Electricity pricing scheme ($/kWh)	Second decimal place in scenario number	Number of deployed turbines	First decimal place in scenario number
WWC	1	0.015 (WWC/REC)	0	0	0
REC	2	0.03 (WWC/REC)	1	1	1
Bitcoin mining	3	0.06 (WWC/REC)	2	2	2
Charging e-cars	4	0.12 (WWC/REC)	3	3	3
		0.03 (Bitcoin mining)	4	4	4
		0.06 (Bitcoin mining)	5	5	5
		0.12 (Bitcoin mining)	6		
		0.02 (charging e-cars)	7		
		0.04 (charging e-cars)	8		
		0.08 (charging e-cars)	9		

Table 4
Criteria for assessing the scenarios.

No.	Criterion
1	General satisfaction of city inhabitants
2	Facilitation of inhabitants' input in urban projects
3	Satisfaction of household customers with the quantity and quality of drinking water
4	Satisfaction of non-household water customers (commercial, industrial, public, firefighting, etc.)
5	Appropriate execution of upstream documents
6	Shift toward sustainable development
7	Reduction of investment costs for the construction of new power plants
8	Reduction of fossil fuel consumption
9	Entire water demand supply
10	Increase in urban water tariff (household and non-household)
11	Increase in electricity tariff (household and non-household)
12	Reduction of investment costs in water and power sector
13	Reduction of operational costs in water and power sector
14	Retraining stringent scenarios in urban water networks (rationing, imposing heavy penalties)
15	Supplying sufficient water with desired pressure in the case study region
16	Ensuring standard water quality in the case study region
17	Reduction of failures and operational costs in WDN
18	Reduction of water loss in WDN
19	Improvement of consumption management in WDN
20	Hydropower energy generation
21	Supporting the power grid with electricity through installing turbines in WDN
22	Stability of the power grid during peak consumption
23	Financial provision and capital attraction in water industry
24	Investment risk reduction in the water industry
25	Increase in return-on-investment rate in water industry
26	Acceleration of investment return in water industry
27	Incentivised and guaranteed purchase of renewable energy by the government
28	Less complexity in technical design (routine nature of design)
29	Less complexity in implementation (routine nature of construction)
30	Conducting research in the field of water and wastewater
31	Less urban conflicts and implementation of the project in low-traffic areas
32	Possibility of facilities procurement domestically
33	Reduction of water bills
34	Reduction of urban traffic and disruption of civil projects
35	Satisfaction of inhabitants from firefighting services
36	Satisfaction of inhabitants from urban landscapes

priority of each criterion for each stakeholder. This assessment was conducted using a Likert scale ranging from 1 to 5. Subsequently, the proposed values were averaged and populated into a stakeholders' utility matrix, denoted as $\mathbf{C}_{m\times n}$, where m represents the number of criteria and n represents the number of stakeholders.

Considering the position and importance of each stakeholder within their social network is crucial for ranking the scenarios. In this context, assigning weights to the stakeholders becomes essential. Utilising information on the powers, interests, and beta centralities of stakeholders from Latifi et al. [38], the weight of each stakeholder was calculated as:

$$w_i = (P_i + I_i)\cdot \mathrm{Cent}_i \tag{2}$$

where, w_i is the weight; P_i is the power; I_i is the interest; and Cent_i is beta centrality of i-th stakeholder, which was determined earlier. All weights were eventually normalised by their averages value. The weights of stakeholders are populated in stakeholders' weight matrix, $\mathbf{W}_{n\times 1}$. The product $\mathbf{C}_{m\times n} \times \mathbf{W}_{n\times 1}$ presents the importance of each criterion, which is indicated by stakeholders' opinions regarding their position in the social network of stakeholders.

Each scenario underwent an assessment against all criteria, taking into account the hydraulic, economic, environmental, and social dimensions associated with each scenario. The outcomes of the scenarios were utilised to quantify their utility against each criterion. To assign utility scores, a mathematical function was defined for each criterion. For instance, the function depicted in Fig. 4a was applied to gauge the 'reduction of failures and operational costs in a WDN.' In this function, if the maximum pressure is lower than a threshold (45 m), the utility is set at 5. As the maximum pressure increases, the utility linearly decreases, and when it exceeds a specified level (70 m in this case study), the utility drops to 1. To quantify the 'satisfaction of household customers,' supply/demand ratio was employed (Fig. 4b), where a ratio equal to or less than one corresponds to the minimum utility. By increasing the ratio up to 1.15, the utility increases linearly from 1 to 5. The energy generated in PaTs aids the grid in sustaining peak consumption situations. Therefore, the utility for 'stability of the power grid during peak consumption' can be calculated as a linear function of generated electricity in PaTs (Fig. 4c), provided it is transmitted to the grid or consumed in WWC facilities or e-car charging. When the PaT energy was consumed for Bitcoin mining, the utility of this criteria was assumed to be at a minimum. The utility of 'acceleration of investment return in water industry' was considered a function of the return of investment period. Since the lifespan of PaTs is around 10 years, if the return on investment exceeds this period, the investment would be inefficacious, resulting in a utility score of 1. The lower the return-on-investment period, the higher the utility (Fig. 4d).

The utility of each scenario against the criteria was populated in a scenarios utility matrix, denoted as $\mathbf{S}_{s\times m}$, in which s is the number of scenarios, and m is the number of criteria. The score for each scenario was calculated as follows:

$$\mathbf{M}_{s\times 1} = \mathbf{S}_{s\times m} \times \mathbf{C}_{m\times n} \times \mathbf{W}_{n\times 1} \tag{3}$$

where, $\mathbf{M}_{s\times 1}$ is a matrix holding the score of each scenario. Ultimately, the scenarios were ranked based on their scores, with the best scenario was selected according to priorities of the stakeholders and their position and weight in social network of stakeholders.

4. Results

This section deals with the outcomes of implementing the proposed methodology in the case study. Running the optimisation model, the optimal configuration for installing PaTs in the WDN was determined. Table 5 showcases the results obtained from optimising the location, type, and working hours of the PaTs. In scenarios where no PaT was installed in the WDN, the pressures in the network are at their highest level, resulting in a maximum daily pressure exceeding 72 m. This elevated pressure led to a supply/demand ratio of 1.16, where the ratio compares the water demand in the WDN to the amount of water available to consumers. In hydraulic modelling, a head-driven consumption relationship was employed, which encompasses both volumetric and pressure-dependent portions of consumption at nodes [57]. Under high-pressure conditions, the pressure-dependent component of consumption increases, resulting in consumption levels exceeding the demand. Low pressure in the network would result in less available water at nodes, leading to a ratio below 1. However, in this case study, the minimum pressure was constrained, ensuring that the available water in the network never fell below the demand.

4.1. Optimal placement of PaTs

By increasing the number of turbines in the WDN, the generated electricity witnessed an increase, accompanied by a decrease in the network pressure. While the maximum pressure was successfully reduced from 72 to 57 m, the minimum pressure remained at 18 m (the minimum allowable pressure) when deploying 5 Pump-*as*-Turbines (PaTs).

4.2. Stakeholders' utilities

Table 6 presents the stakeholders' utility matrix, essentially creating a matrix that underscores the importance of each criterion for every stakeholder. For example, the criterion 'satisfaction of household customers with the quantity and quality of drinking water' holds substantial importance for *WWC*, *MoE*, and *Cnsm*, with scores of 4.67, 4.22, and

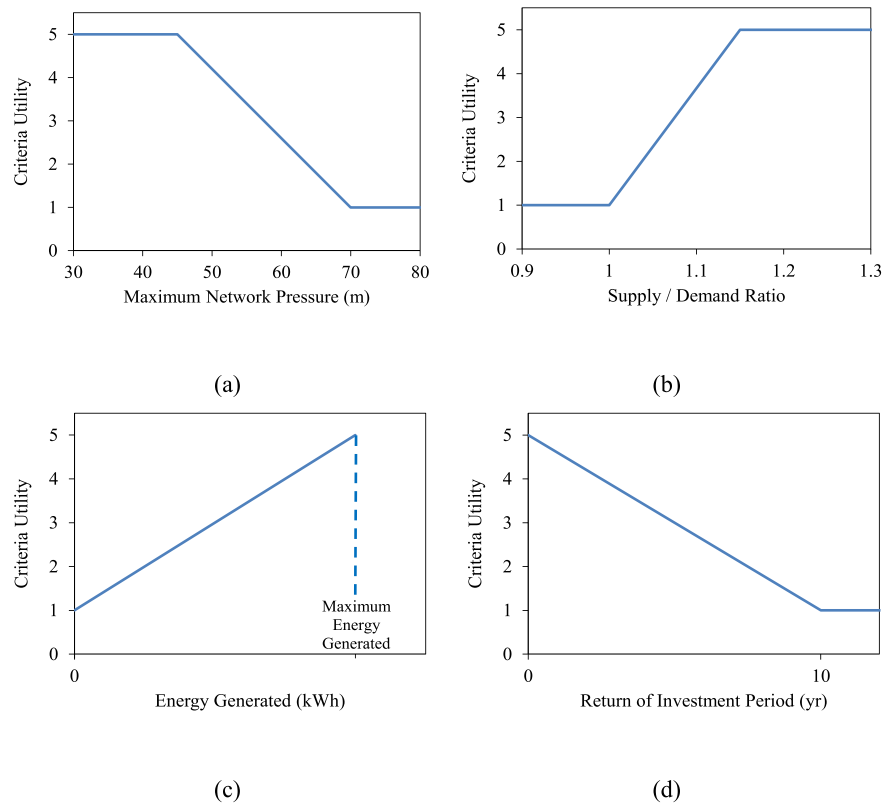

Fig. 4. Criteria utility functions for (a) reduction of failures and operational costs; (b) satisfaction of household customers; (c) stability of the power grid during peak consumption; and (d) acceleration of investment return in water industry.

Table 5
The results of optimising 0–5 PaTs in the case study.

Number of turbines	Generated electricity (kWh/yr)	Minimum water pressure in WDN (m)	Mean water pressure in WDN (m)	Maximum water pressure in WDN (m)	Supply/demand ratio
0	0	22.3	36.3	72.4	1.16
1	102,859	21.1	35.4	67.7	1.11
2	137,307	19.8	34.8	63.9	1.07
3	156,132	18.5	34.2	60.2	1.05
4	186,592	18.2	33.7	58.1	1.03
5	212,189	18.0	33.4	57.0	1.03

4.00, respectively. The first two stakeholders play crucial roles in the provision, while the latter benefits significantly from the consumption of drinking water. Similarly, 'reduction of investment costs for the construction of new power plants' is a significant criterion for *MoE*, *REC*, and Planning and Budget Organisation (*P&B*) (representing the government), with values of 4.89, 4.67, and 4.56, respectively. This underscores the prudent decision to avoid additional investments for depeaking plans. The utilisation of micro-turbines as a renewable energy source, aimed at reducing the use of fossil fuels, emphasises the importance of 'reduction of fossil fuel consumption,' with a value of 3.67 for the Environment Protection Agency (*EPA*).

'Avoiding stringent scenarios in urban water networks' holds considerable importance for *Cnsm* and *NGO*, given their substantial susceptibility to strict regulations within the WDN. Furthermore, the criterion 'reduction of failures and operational costs in WDN,' vital for preventing failures and disruptions in the WDN, holds high importance for *WWC* (4.89), with *Cnsm* following closely at 4.38, representing the primary drinking water customers. *MoE* and.

REC expressed a strong interest in the criterion 'Supporting the power grid with electricity through turbine installation' due to its potential to alleviate strain on the power grid during peak consumption periods. The prospect of an 'Increase in return-on-investment rate in the water industry' is appealing to investors and venture capitalists, making this criterion significant for both *MoE* (4.67) and *BFI* (3.44). Furthermore, 'Reduced complexity in technical design' and 'Simplified implementation' streamline project execution, thereby rendering these criteria vital for *Cntr* (3.56) and *Cnsl* (4.22), respectively.

Taking into account the power, interest, and beta centrality of each stakeholder, their weights were calculated through Eq. (2). The normalised weights of stakeholders are outlined in Table 1. In this case study, *WWC*, *MoE* and City Council (*CC*) emerged as the stakeholders with highest weights in decision making, respectively. Conversely, the stakeholders with the lowest weights were the Health Organisation (*HO*), Firefighting Organisation (*FO*), and Landscape (*Lan*), respectively.

4.3. Scenario ranking

As explained in the Methodology Section, variations among scenarios primarily revolve around the number of deployed micro-turbines, the pricing schemes for energy generation and sales, as well as the allocation of electricity to four distinct purposes. Table 7 encompasses all 84 scenarios, featuring each scenario number (as defined in Table 3) alongside the corresponding scores derived from the $\mathbf{M}_{s\times1} = \mathbf{S}_{s\times m} \times \mathbf{C}_{m\times n} \times \mathbf{W}_{n\times1}$ equation. Scenario #225, which involves the use of 5 micro-turbines, employs the second-highest pricing scheme (0.06 $/kWh), and sells electricity to the grid, achieved the highest score at 6466.8. The second-highest score is attributed to scenario #365, which deploys the maximum number of micro-turbines, focuses on mining Bitcoins, and prices energy based on the highest Bitcoin value over a 3-year period (0.12 $/kWh), obtaining a score of 6434.3. Scenarios #364 and #363, involving allocating energy generated at 4 and 3 turbines to Bitcoin mining, stood at 3rd and 4th place, respectively. Scenario #235,

Tables 6
Stakeholders' utility matrix, $\mathbf{C}_{m\times n}$.

Criteria	P&B	Gov	MoE	RWBC	REC	WWC	Parl	CC	Mun	FO	Lan	HO	BFI	Cntr	Cnsl	EPA	NGO	Cnsm
General satisfaction of the city inhabitants	4.11	3.78	4.33	3.67	3.78	4.67	3.89	4.22	4.00	3.44	3.33	3.44	2.22	2.67	2.67	2.32	3.00	3.38
Facilitation of inhabitants input in urban projects	2.44	2.33	2.78	2.22	2.22	3.22	2.78	2.89	2.67	2.00	2.11	2.11	1.89	1.50	1.75	1.89	3.00	2.38
Satisfaction of household customers with the quantity and quality of drinking water	3.44	3.44	4.22	3.78	2.00	4.67	3.33	3.56	2.67	1.78	1.89	3.44	1.38	2.25	2.88	3.33	3.00	4.00
Satisfaction of non-household water customers (commercial, industrial, public, firefighting, etc.)	3.22	3.11	3.89	3.33	1.78	4.11	2.89	3.11	2.89	2.56	2.89	2.22	1.50	2.25	2.38	2.44	2.56	3.00
Appropriate execution of upstream documents	4.33	3.22	4.56	3.67	2.89	4.22	4.22	3.89	2.56	2.56	2.00	2.11	2.67	2.11	2.44	2.56	2.11	1.88
Shift toward sustainable development	4.56	3.11	4.56	4.00	3.67	4.11	4.22	3.56	3.33	2.67	2.56	2.67	2.11	1.89	2.56	3.00	2.78	2.88
Reduction of investment costs for the construction of new power plants	4.56	2.89	4.89	3.78	4.67	3.56	4.11	3.11	2.56	1.67	1.44	1.67	2.00	2.78	2.78	2.89	2.44	2.00
Reduction of fossil fuel consumption	3.78	2.56	4.22	2.67	3.56	3.11	3.78	3.11	3.00	1.67	1.78	2.67	1.89	1.56	2.11	3.67	2.67	2.25
Supply of entire water demand	3.89	3.67	4.89	4.11	2.33	4.78	3.67	3.89	3.00	2.00	2.00	2.22	1.56	2.44	2.67	2.89	2.89	3.88
Increase in urban water tariff (household and non-household)	3.67	2.89	4.67	3.78	1.89	4.56	3.67	3.11	2.44	1.56	1.56	1.56	2.22	2.11	2.56	2.22	2.22	3.38
Increase in electricity tariff (household and non-household)	3.89	2.78	4.67	2.89	4.44	2.67	3.78	3.11	2.44	1.67	1.56	1.56	2.22	2.11	2.56	2.22	2.11	2.75
Reduction of investment costs in water and power sector	4.11	3.11	4.78	4.11	4.33	4.67	4.33	3.78	2.44	1.67	2.00	1.78	2.67	2.89	2.67	2.44	2.44	2.38
Reduction of operational costs in water and power sector	4.22	2.89	4.89	4.11	4.33	4.89	4.22	3.67	2.33	1.56	2.11	1.78	2.00	2.00	2.44	2.11	2.44	2.50
Avoiding stringent scenarios in urban water networks (rationing, imposing heavy penalties)	2.33	2.44	3.67	3.11	1.89	3.89	2.89	2.56	1.78	1.44	1.78	1.44	1.33	1.67	1.89	1.78	1.89	3.25
Supplying sufficient water with desired pressure in the case study region	3.11	3.56	4.33	3.67	2.00	4.89	3.44	3.56	2.89	2.44	2.00	2.56	1.56	2.33	2.67	2.67	2.89	3.88
Ensuring standard water quality in the case study region	3.00	3.56	4.33	4.00	2.00	4.89	3.56	3.78	3.00	1.78	1.78	3.11	1.78	2.67	3.00	3.00	3.00	4.38
Reduction of failures and operational costs in WDN	3.44	3.22	4.22	3.00	1.78	4.89	3.22	3.22	2.89	2.11	1.56	2.11	1.44	2.11	2.33	2.33	2.78	4.00
Reduction of water loss in WDN	3.33	2.56	4.44	3.89	1.67	4.67	2.89	2.78	2.33	1.56	1.56	1.56	1.33	2.33	2.33	2.11	2.22	2.88
Improvement of consumption management in WDN	3.11	2.78	4.67	3.44	1.78	4.89	3.11	3.00	2.56	1.33	1.33	1.56	1.33	2.44	2.33	2.22	2.89	3.13
Hydropower energy generation	4.00	1.00	4.00	1.00	4.00	5.00	3.00	2.00	2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Supporting the power grid with electricity through installing turbines in WDN	2.89	2.11	4.00	2.89	3.33	3.89	2.56	2.11	1.78	1.33	1.22	1.33	1.22	2.22	2.33	2.11	2.00	2.25
Stability of the power grid during peak consumption	3.44	3.44	4.89	3.22	4.78	3.67	3.44	3.11	2.22	1.89	1.56	1.89	1.78	1.78	2.11	2.00	2.56	2.88
Financial provision and capital attraction in water industry	4.33	3.00	4.89	4.00	2.11	4.44	3.67	2.78	1.89	1.11	1.33	1.44	2.67	2.67	2.78	1.44	2.11	2.00
Investment risk reduction in the water industry	4.00	2.89	4.67	4.33	2.11	4.33	3.67	2.56	1.67	1.11	1.11	1.44	2.78	3.11	2.56	1.33	1.67	1.88
Increase in return-on-investment rate in water	3.89	2.67	4.67	3.89	2.11	4.11	3.56	2.78	1.78	1.22	1.22	1.33	3.44	3.44	3.11	1.56	1.89	2.00
Acceleration of investment return in water industry	3.89	2.67	4.67	3.89	2.11	4.11	3.56	2.78	1.78	1.22	1.22	1.33	3.44	3.44	3.11	1.56	1.89	2.00
Incentivised and guaranteed purchase of renewable energy by the government	3.67	2.89	4.44	3.67	3.33	4.22	3.56	2.56	1.78	1.11	1.11	1.33	2.22	2.78	2.78	1.78	1.78	1.88
Less complexity in technical design (routine nature of	2.89	2.56	3.89	3.11	3.00	4.33	2.11	2.00	1.89	1.22	1.22	1.22	2.00	3.56	3.33	1.78	1.44	1.88
Less complexity in implementation (routine nature of construction)	3.11	2.56	4.11	3.22	3.00	4.56	2.00	2.00	2.33	1.33	1.22	1.33	1.78	3.78	4.22	1.67	1.56	2.00
Conducting research in the field of water and wastewater	2.78	2.00	4.33	3.11	1.56	4.33	2.33	1.78	1.78	1.67	1.67	1.67	1.33	1.44	2.56	1.56	2.11	1.63
Less urban conflicts and implementation of the project in low-traffic areas	2.22	2.78	3.78	2.89	2.00	4.56	2.22	2.89	3.67	2.00	1.44	1.44	1.44	3.67	3.11	1.78	2.33	2.50
Possibility of facilities procurement domestically	3.89	2.89	4.56	3.44	3.67	4.22	4.00	3.11	2.22	1.56	1.33	1.44	2.11	3.11	2.78	2.11	2.11	1.75
Reduction of water bills	3.00	2.78	4.22	3.33	1.67	3.67	3.11	2.78	1.89	1.56	1.67	1.56	1.44	1.67	2.11	2.00	2.44	3.38
Reduction of urban traffic and disruption of civil projects	2.78	3.22	3.44	3.11	2.22	4.22	2.89	3.67	4.00	2.44	1.89	1.44	1.22	2.78	2.44	1.56	2.78	3.38
Satisfaction of inhabitants from firefighting services	2.25	3.13	1.88	1.88	1.25	2.00	2.75	3.25	3.75	4.63	1.63	1.13	1.13	1.13	1.38	1.25	2.63	3.25
Satisfaction of inhabitants from urban landscapes	2.38	3.25	2.13	2.50	1.88	2.00	3.00	3.88	4.38	2.13	4.00	1.50	1.38	1.63	1.63	2.63	3.00	3.38

Table 7
Total score of the scenarios.

Scenario number			Score	Scenario number			Score	Scenario number			Score	Scenario number			Score
Electricity allocation	Electricity pricing scheme	Number of deployed turbines		Electricity allocation	Electricity pricing scheme	Number of deployed turbines		Electricity allocation	Electricity pricing scheme	Number of deployed turbines		Electricity allocation	Electricity pricing scheme	Number of deployed turbines	
1	0	0	4802.3	2	0	0	5004.9	3	4	0	5381.7	4	7	0	4396.2
1	0	1	5892.0	2	0	1	6118.0	3	4	1	6081.2	4	7	1	5349.2
1	0	2	5903.2	2	0	2	6148.1	3	4	2	6022.8	4	7	2	5346.5
1	0	3	5863.7	2	0	3	6127.0	3	4	3	5980.2	4	7	3	5304.6
1	0	4	5887.1	2	0	4	6116.1	3	4	4	5865.2	4	7	4	5241.7
1	0	5	5967.2	2	0	5	6201.6	3	4	5	5804.8	4	7	5	5247.7
1	1	0	4681.9	2	1	0	4839.6	3	5	0	5381.7	4	8	0	4342.5
1	1	1	5887.3	2	1	1	6068.4	3	5	1	6183.8	4	8	1	5457.2
1	1	2	5987.2	2	1	2	6187.3	3	5	2	6184.8	4	8	2	5528.1
1	1	3	6023.0	2	1	3	6241.6	3	5	3	6188.0	4	8	3	5546.7
1	1	4	6054.3	2	1	4	6283.3	3	5	4	6135.2	4	8	4	5563.5
1	1	5	6120.1	2	1	5	6354.5	3	5	5	6110.9	4	8	5	5612.3
1	2	0	4516.6	2	2	0	4674.4	3	6	0	5381.7	4	9	0	4342.5
1	2	1	5810.8	2	2	1	5991.9	3	6	1	6317.7	4	9	1	5566.2
1	2	2	5965.4	2	2	2	6165.5	3	6	2	6375.9	4	9	2	5692.4
1	2	3	6044.5	2	2	3	6263.1	3	6	3	6417.2	4	9	3	5751.3
1	2	4	6133.9	2	2	4	6362.9	3	6	4	6420.0	4	9	4	5824.3
1	2	5	6232.4	2	2	5	6466.8	3	6	5	6434.3	4	9	5	5908.2
1	3	0	4210.9	2	3	0	4341.8								
1	3	1	5611.1	2	3	1	5765.4								
1	3	2	5813.7	2	3	2	5987.0								
1	3	3	5925.9	2	3	3	6117.5								
1	3	4	6062.6	2	3	4	6264.7								
1	3	5	6192.7	2	3	5	6400.4								

which proposes transmitting the energy produced in 5 turbines to the grid at the highest price, gained the 5th highest score. The top 5 scenarios were summarised and presented in Table 8.

Comparing various ways of allocating electricity, the best scenarios were those in which the energy was sold to the national grid. Although both grid sales and Bitcoin mining offer the same pricing, scenarios that involve supplying the grid receive more substantial support from influential stakeholders. Under favourable conditions in the Bitcoin market, Bitcoin mining emerges as the second-best option for energy allocation. Allocating energy for sale to *WWC* does not rank high because this stakeholder prefers purchasing energy from the grid with subsidies rather than relying on micro-turbines. The least preferred option is using the energy for charging electric cars, possibly influenced by the lower popularity of electric cars in the case study region and the availability of extremely cheap domestic power for e-car charging.

Furthermore, various pricing schemes for the generated energy were compared. In scenarios where the energy is sold to the grid, those with prices double the current incentive price obtained the highest scores. Although the highest price, four times the current price, may be appealing to investors, it lacks support from the government (*P&B*, *MoE*, and *CCW*), which is a crucial stakeholder in the social network. Despite Bitcoin mining scenarios securing the 2nd, 3rd, and 4th positions, it is essential to acknowledge that these scenarios are contingent on a high valuation of Bitcoin.

In all states, employing the maximum number of PaTs garnered the highest score, as these scenarios yield the maximum electricity and associated benefits. However, the number of turbines is limited to five to ensure that the minimum pressure within the WDN remains within the allowable range.

To assess the impact of stakeholders' weight on the results, the top three scenarios were identified using weights ranging from 0.5 to 2 times those employed in the current study. Table 9 displays the outcomes of the sensitivity analysis conducted for four stakeholders. The findings suggest that, in most instances, the top three scenarios remain consistent even when significant changes are made to stakeholder weights. However, a notable exception arises when the weight of *WWC* (the stakeholder with the highest weight) is halved, resulting in a different third-best scenario compared to other cases. These results demonstrate that, in this particular case study, the final scenario is relatively insensitive to variations in stakeholder weights.

Table 9
The top three scenarios, in case of changing each stakeholder's weight (w_i).

Stakeholder	Weight				
	0.5 w_i	0.75 w_i	w_i	1.5 w_i	2 w_i
WWC	225	225	225	225	225
	365	365	365	365	365
	363	364	364	364	364
REC	225	225	225	225	225
	365	365	365	365	365
	364	364	364	364	364
BFI	225	225	225	225	225
	365	365	365	365	365
	364	364	364	364	364
Cnsm	225	225	225	225	225
	365	365	365	365	365
	364	364	364	364	364

5. Discussion and conclusion

Stakeholders wield significant influence over the outcome of energy harvesting projects in WDNs. For example, a scenario offering considerable technical and economic benefits may falter if it lacks sufficient support from influential stakeholders. Thus, when determining the optimal placement of PaTs within a WDN, it is essential to consider the powers, interests, perspectives, and preferences of the stakeholders. This paper proposes a novel methodology to identify the optimal scenario for the implementation of micro-turbines, specifically PaTs, in a WDN with the highest consensus among the stakeholders. By employing a simulations-optimisation model, the optimal location, type, and operation hours for micro-turbines were determined to maximise the generated energy while ensuring that the minimum pressure within the WDN remains above a specified level. A total of 84 scenarios were devised, considering the number of installed turbines, energy allocation, and pricing schemes for PaTs. To assess these scenarios, 36 criteria were employed. Stakeholders' perspectives on these criteria were quantified through interviews with their representatives, resulting in a stakeholders' utility matrix. Additionally, weights were assigned to each stakeholder based on the results of SA and SNA analysis, forming a stakeholders' weight matrix. The utility of each scenario concerning the criteria was then calculated in a scenarios' utility matrix. The scenarios were subsequently ranked based on the product of these three matrices, yielding a comprehensive evaluation.

The stakeholders collectively constitute an intricate social network responsible for water and energy management within a WDN. Through interviews, water experts and stakeholders' delegates shared insights into the roles of various stakeholders and the challenges associated with energy harvesting projects in a WDN. The *WWC* emerged as a central stakeholder within the social network, possessing significant power and interest. However, despite its influential position, *WWC* lacks the motivation to procure energy generated by micro-turbines due to its access to affordable, subsidised electricity from the grid. Consequently, *WWC* and even the government are unlikely to provide financial backing for such projects. In this context, *BFI* stand out as the sole stakeholders capable of offering financial support for renewable energy production projects. Stakeholder analysis reveals that *BFI* is a peripheral stakeholder, characterised by low power, interest, and access to information in energy management within a WDN. The findings of this research highlight the role of peripheral yet significant stakeholders in supporting this project. For instance, providing *BFI* with greater access to information to empowers them to assume a central role and make well-informed decisions regarding investments in renewable energy production within WDNs. On the other hand, *REC* emerges as a stakeholder

Table 8
Summary of top 5 scenarios.

Rank	Scenario number	Number of deployed turbines	Electricity allocation	Electricity price ($/kWh)	Generated electricity (kWh/yr)	Minimum water pressure in WDN (m)	Mean water pressure in WDN (m)	Maximum water pressure in WDN (m)	Supply/demand ratio
1	#225	5	Selling the generated electricity to REC	0.06	212,189	18	33.4	57	1.03
2	#365	5	Bitcoin mining	0.12	212,189	18	33.4	57	1.03
3	#364	4	Bitcoin mining	0.12	186,592	18.2	33.7	58.1	1.03
4	#363	3	Bitcoin mining	0.12	156,132	18.5	34.2	60.2	1.05
5	#235	5	Selling the generated electricity to REC	0.12	212,189	18	33.4	57	1.03

with a high interest in energy harvesting in WDNs, as energy generated by small generators aids in mitigating peak electricity consumption during high-demand periods.

Among the local stakeholders, *CC* and *Mun* have an intermediary role, bridging the gap between national/regional stakeholders and the end consumers. They are inclined to expedite the progress of renewable energy projects by facilitating the necessary permits. Simultaneously, they face the challenge of preventing disruptions caused by civil projects. *Cnsm*, on the other hand, are the stakeholders most directly impacted by these plans but possess limited influence to articulate their opinions.

Despite the perceived sustainability of PaTs as sources of electrical energy, it is important to acknowledge their limitations. Primarily, PaTs are not engineered for reverse flow, rendering them less efficient compared to conventional hydro-electric turbines. Although, PaTs offer a cost-effective option for energy harvesting in WDNs due to their lower investment costs.

Furthermore, employing PaTs for energy generation may disrupt flow regulation in the WDN. However, hydraulic and electric regulation mechanisms should be employed to ensure suitable flow regulation in the network [58].

Additionally, limited research has been conducted to identify the technical specifications of PaTs, through their pump characteristics. This shortcoming can be addressed by utilising facilities that have undergone testing under both laboratory and field conditions. Therefore, evaluating the investment feasibility and economic returns of PaTs requires thorough consideration.

Beyond these technical challenges, soliciting clear expressions of views from experts and delegates regarding stakeholders' interests, especially their own organisations, within such a complex network, presents a challenge. Essentially, there is inherent uncertainty in interview outcomes, which could impact the study's final results. Furthermore, the social network of stakeholders in each case study is unique, necessitating careful consideration of key assumptions, particularly when generalising the methodology to new cases.

This research highlights that stakeholders and their utilities should be taken into account when selecting the optimal scenario for energy harvesting in WDNs, complementing the traditional focus on techno-economic aspects. The methodology proposed in this paper quantifies the influence of stakeholders, ranking scenarios based on criteria crucial to their interests. The outcomes of this research provide decision-makers and policymakers with valuable insights to opt-in scenarios with maximal stakeholder support and minimal dissatisfaction, thereby enhancing the likelihood of success for such projects.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Milad Latifi and Reza Kerachian report financial support was provided by Iran National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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