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Integrated water–energy–carbon nexus optimisation of coastal urban water systems: linking hydraulic modelling and policy for sustainable management

Surasak Janchai [1], Nat Nakkorn [1✉], Suparatchai Vorarat [1], and Prayuth Rittidatch [1]

[1]College of Engineering and Technology, Dhurakij Pundit University, Bangkok 10210, Thailand

ARTICLE INFO	ABSTRACT
Paper Type: Research Paper **Corresponding author:** N. Nakkorn ✉ nat.nak@dpu.ac.th	This study addressed the high energy consumption, greenhouse gas emissions, and infrastructure strain in urban water distribution systems, using Pattaya City, Thailand, as a case study. It establishes an integrated Water–Energy–Carbon (WEC) framework that combines EPANET hydraulic modelling, SCADA monitoring, and GIS spatial analysis to identify operational inefficiencies and evaluate low-carbon enhancement strategies. The research assessed five distribution zones over 20 years, comparing a baseline scenario with an efficiency-enhancement scenario. The proposed improvements included implementing variable-frequency drive (VFD) control, optimising pump schedules, and rehabilitating targeted pipes. Using actual SCADA data and Thailand's grid emission factor, the analysis quantified electricity intensity and carbon emissions. The results demonstrated that the integrated measures could achieve a 32.6% reduction in total pumping energy and a 30.0% decrease in annual CO_2 emissions (approximately 540 tCO₂e/year, or 10,800 tCO₂e over two decades), all while maintaining a minimum service pressure of 0.5 bar. The WEC framework provides a practical decision-support tool that aligns utility operations with national decarbonisation goals and Sustainable Development Goal 6. It enables water utilities to optimise pump scheduling, prioritise pipe rehabilitation, and lower operating costs. For policymakers, it offers a basis for designing effective tariffs, targeting infrastructure investments, and embedding carbon mitigation into urban water strategies.
Highlights	• Good water governance can prevent future crises in this sector. • The foresight approach can evaluate and analyze the entirety of a system. • using the foresight technique to realize water governance through critical evaluation

1. Introduction

Sea-level rise, erratic rainfall patterns, and sudden extreme weather events are all contributing to the growing vulnerability of large urban coastal cities to the effects of climate change. These factors, combined with the rapid expansion of urban areas, population growth, and the continued growth of seasonal tourism, are placing significant pressure on local environments and water supply systems. In Thailand, major coastal cities such as Pattaya, Hua Hin, and Phuket face particularly severe challenges, including long-distance water pumping, high-altitude delivery, and ageing infrastructure. These challenges, combined with high energy consumption and unavoidable carbon emissions, result in increased

environmental and economic costs for water supply operations over the long term (Friedrich et al., 2009; Huang et al., 2023; Kenway et al., 2019). Research on the water–energy nexus (WEN) has long recognised the interdependence between water delivery efficiency and energy demand. Early studies highlighted the potential for hydraulic optimisation and operational adjustments to improve efficiency (Chazarra et al., 2017; Lee et al., 2017). More recently, the WEN framework has evolved into the water–energy–carbon (WEC) nexus, which explicitly incorporates carbon emissions into performance metrics and policy objectives (Gómez Gardars et al., 2022; Han et al., 2023). This conceptual progression enables research to move beyond purely technocratic

efficiency considerations towards integrated approaches that balance service reliability, energy savings, and decarbonisation goals. Several empirical applications have demonstrated the potential of the WEC framework in practice. Chhipi-Shrestha et al. (2017) employed a system dynamics model to capture interdependencies in Bangkok, while Ociepa-Kubicka et al. (2024) quantified avoidable carbon emissions from leakage and pipeline friction. Bi et al. (2020) applied evolutionary optimisation to pressure and pumping schedules, achieving substantial reductions in energy consumption and emissions. Case studies in Southeast Asia further illustrate that poor monitoring, limited automatic pressure control, and reliance on low-resolution SCADA data remain major obstacles to efficiency (Rambau et al., 2024; Sadek et al., 2022). At the same time, studies of Mediterranean and Asian tourist destinations highlight that peak-season demand surges intensify both water losses and energy requirements, placing additional stress on existing infrastructure (Jiménez-Islas et al., 2025; Pásková et al., 2024).

In Thailand, Srisuwan (2024) documented how high-altitude service zones amplify pumping needs and leakage risks, while Yin et al. (2024) and Kasalkar et al. (2025) showed that overproduction of treated water directly results in unnecessary energy use and greenhouse gas emissions. Together, these findings reveal persistent structural carbon inefficiencies that remain underexplored in the literature. Governance and technological innovations have been suggested as potential solutions. Cai et al. (2021) demonstrated the feasibility of solar-assisted pumping and combined heat and power systems in coastal towns, while Alawad et al. (2023) investigated wave-driven desalination. The utilisation of hybrid water grids for energy storage was recommended by Rahim (2019), and Buller et al. (2022) described Thailand's Sirindhorn floating solar hybrid project as an example of renewable energy integration that is compatible with the World Energy Network (WEN).

Nevertheless, the extent to which translation into operational frameworks and policy instruments has been achieved has been limited, despite significant progress. Fragmented institutions and inadequate regulatory coordination continue to restrict coherent planning at the governance level (Taniguchi et al., 2017). The institutional fragmentation in Thailand is particularly severe, as water and energy agencies frequently operate in isolation, which impedes the development of comprehensive responses to infrastructure and climate challenges. Although the WEC nexus is receiving growing international attention, its application in Thailand's coastal tourist cities remains limited. Few studies explicitly link hydraulic performance, SCADA-based energy analytics, and carbon accounting within a single optimisation framework. Most previous work has treated water, energy, and carbon as separate issues, without systematically connecting technical inefficiencies such as leakage, overproduction, and friction losses to their carbon implications.

This study therefore develops an integrated water–energy–carbon (WEC) optimisation framework tailored to coastal urban water distribution systems in Thailand, with Pattaya serving as the case study. The framework combines EPANET-based hydraulic simulation, SCADA-derived operational data, and GIS spatial analysis within a multi-objective optimisation

process (NSGA-II). The objective is to evaluate targeted strategies for energy and carbon reduction, while explicitly linking technical optimisation with investment planning and policy design.

2. Materials and Methods

This study develops an integrated Water–Energy–Carbon (WEC) optimisation framework for coastal urban water systems, in which the interdependencies between hydraulic performance, energy consumption, and carbon emissions are explicitly modelled. The framework couples hydraulic network simulation, energy-flow assessment, and carbon accounting within a single, iterative decision-support workflow (Fig. 1). Data for the framework were drawn from three sources: (i) supervisory control and data acquisition (SCADA) operational records (flows, pressures, pump power and run-time) collected by the Provincial Waterworks Authority (PWA) for the five distribution zones at 15–30 min resolution; (ii) the hydraulic network inventory and EPANET input files pipe length, diameter, material, roughness coefficients, node, elevations, demand patterns, pump and PRV settings provided by PWA; and (iii) time-varying grid CO_2 emission factors, EF_{grid} (t), issued by the Thailand Greenhouse Gas Management Organization (TGO, 2023). To ensure coherence between research objectives and analytical design, the study's research questions are mapped to WEC dimensions, model variables, and key performance indicators (KPIs) in Table 1.
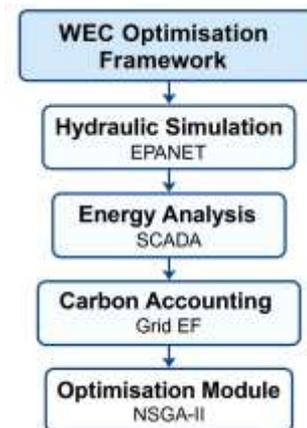

Fig.1 Integrated WEC optimisation framework for coastal urban water systems

By embedding real operational data, time-varying energy factors, and system constraints, the approach ensures both technical accuracy and practical applicability. The methodology is structured into five main stages:

2.1 Data acquisition

Water distribution network data, including pipe characteristics, node elevations, and demand patterns were obtained from the Provincial Waterworks Authority of Thailand. Energy consumption and operational data were derived from Supervisory Control and Data Acquisition (SCADA) records provided by PWA's regional offices. Grid emission factors (EF_{grid}) were sourced from the Thailand Greenhouse Gas Management Organisation (TGO, 2023), by national GHG inventory methodologies.

Table 1 Mapping of Research Questions to WEC Dimensions, Model Variables, and Key Performance Indicators (KPIs)

Research Question	WEC Dimension	Model Variable(s)	KPI	Data Source	Unit
How can operational inefficiencies be identified and reduced in coastal urban water systems?	Water	Pressure, Flow, Leakage probability	Pressure compliance (%), Leakage reduction (%)	EPANET simulation; SCADA pressure sensors	m, %, probability
How can energy consumption be minimised without compromising service reliability?	Energy	Pump scheduling, Energy input/output balance	Energy intensity (kWh/m³), Energy reduction (%)	SCADA operational data; Electricity bills	kWh, %, m³
How can CO_2 emissions from pumping operations be reduced in line with national decarbonisation targets?	Carbon	Electricity consumption (E_{elec}), Grid emission factor (EF_{grid})	Annual CO_2 (t/year), CO_2 reduction (%)	GO emission database (2024); Utility electricity records	t CO_2/year, %

Based on this mapping, Table 2 specifies how each WEC dimension was operationalised in this study, detailing the relevant variables, data sources, and analytical methods used for performance evaluation.

Table 2 Operationalisation of WEC Dimensions in the Modelling Framework

| WEC Dimension	Operational Definition in This Study	Data Source	Analytical Method
Water	Hydraulic pressure, flow distribution, leakage probability	EPANET simulation, SCADA data	Baseline and scenario simulations
Energy	Pump energy input/output, losses (leakage, friction, sedimentation)	SCADA kWh readings, EPANET headloss	Energy balance analysis
Carbon	CO_2 emissions from electricity use for pumping	EF_{grid} from TGO, E_{elec} from SCADA	CO_2 accounting via Equation (3)

2.2 Hydraulic simulation

EPANET 2.2 was applied to simulate network hydraulics under baseline and alternative operational scenarios. Model calibration was performed using measured pressures and flows, with Mean Absolute Percentage Error (MAPE) maintained below 5% to ensure accuracy.

2.3 Model calibration and sensitivity analysis

To ensure that the simulated values closely matched the field observations, EPANET 2.2 was calibrated against the measured pressures and flows from the SCADA system for each distribution zone. The accuracy of the model was evaluated using the Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), and Nash–Sutcliffe Efficiency (NSE). The MAPE was maintained below 5% in all calibration zones, and the NSE surpassed 0.9, suggesting a solid replication of real-world operating conditions in both the baseline and alternative scenarios. Until convergence was achieved without compromising physical plausibility, calibration adjustments were restricted to hydraulically defensible parameters, specifically pipe roughness coefficients, nodal demands, and pump curves. To quantify the relative impact of critical model parameters on hydraulic, energy, and carbon performance, a local sensitivity analysis was conducted following calibration. The remaining parameters were maintained at their calibrated values, while four parameters were perturbed within ±20% of their values. Pipe roughness (C) denotes the Hazen–Williams coefficient, a dimensionless measure of internal pipe condition and resistance to flow; typical ranges are 80–140 for cast iron and 120–150 for PVC. The pressure–leakage exponent (N1) is a dimensionless quantity that represents the responsiveness of leakage to pressure changes; values generally lie between 0.5 and 1.5 in field and empirical studies (Dundović et al., 2022). Pump efficiency (η), expressed as a percentage, is the ratio of sound hydraulic energy to electrical input; municipal centrifugal pumps typically operate between 55% and 85%. Demand variation (DV) is a dimensionless scaling factor applied to the baseline demand profile to capture seasonal or tourism-driven fluctuations and was modelled within ±20% of baseline demand. Performance responses were evaluated using pressure compliance (percentage of nodes meeting the minimum service pressure of 0.5 bar), energy intensity (kWh/m³), leakage reduction (%), and CO_2 reduction (%) computed using the grid-emission-factor formulation in Equation (3). The analysis revealed that N1 had the most significant influence on leakage-related indicators. At the same time, η dominated energy and carbon outcomes, and C and DV displayed moderate but non-negligible effects across all indicators. Results are summarised in Fig. 2, whose caption has been shortened accordingly to avoid redundancy with the Methods text.

Fig.2 Sensitivity analysis results for C, N1, η, and DV on pressure compliance, energy intensity, leakage reduction, and CO₂ reduction
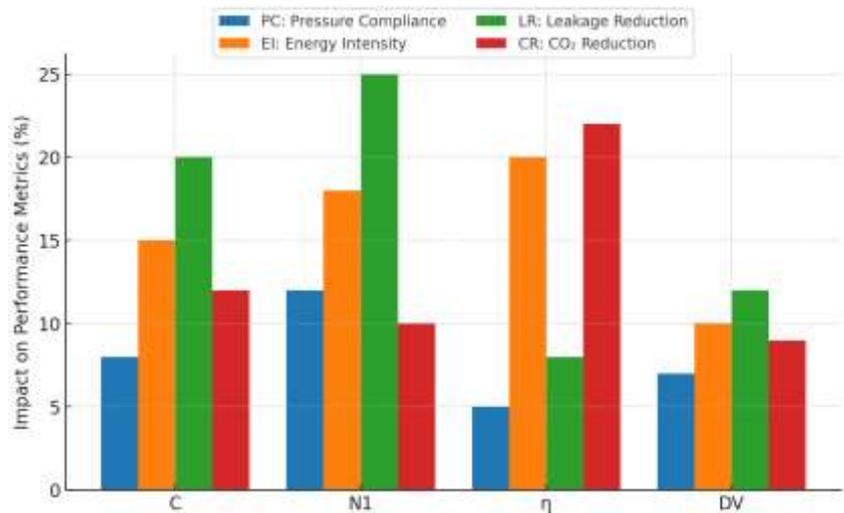
2.4 Energy analysis

The total system energy input (E_{in}) equals the total energy output (E_{out}), expressed as

$$E_{in} = E_{out} \tag{1}$$

Following standard energy-balance formulations for water distribution networks, the total system energy input equals the total energy output at the network boundary, reflecting conservation of energy at the system scale (Cabrera et al., 2010; Lenzi et al., 2013).

Where:

$$E_{out} = E_u + E_i + E_f + E_s \tag{2}$$

The decomposition of output energy into delivered energy and dissipation terms follows established energy-audit practice for water networks (Cabrera et al., 2010; Lenzi et al., 2013; Lipiwattanakarn et al., 2021).

In this framework, the electricity consumption term $E_{elec}(t)$ refers exclusively to the actual electrical energy used for pumping operations, excluding any components already accounted for in E_{out}. This separation ensures that losses such as leakage, friction, or sedimentation are represented in E_i, E_f and E_s are not double-counted in the carbon emission calculation.

2.5 Carbon emission estimation

The estimation of carbon dioxide equivalent (CO₂eq) emissions associated with potable water production is based on anticipated reductions in electricity consumption resulting from improved distribution efficiency, specifically through the replacement of ageing water pipelines. The calculation employs the unit production cost of potable water, using electricity consumption per unit volume as a proxy activity factor. CO₂ emissions are computed using the following equation:

$$CO_2 Total = \sum_t (E_u + E_i + E_f + E_s)_t \ x \ EF_{grid}(t) \tag{3}$$

With these methodological components established, the integrated WEC optimisation framework was applied to five distinct water distribution zones in Pattaya City. The hydraulic, energy, and carbon performance of each zone was evaluated under baseline and alternative improvement scenarios, using the mapped KPIs from Table 1 and the operational definitions from Table 2. The subsequent section presents the baseline results, scenario evaluations, and trade-off analyses, highlighting how the proposed framework identifies inefficiencies, quantifies potential gains, and supports targeted intervention planning.

2.6 Multi-objective optimisation using NSGA-II

To identify optimal operational strategies that minimise both energy use and CO₂ emissions while maintaining hydraulic service standards, a Non-dominated Sorting Genetic Algorithm II (NSGA-II) was integrated within the WEC optimisation framework. The algorithm was employed to explore trade-offs between pump scheduling, pressure zone setpoints, and rehabilitation actions under multi-objective criteria. Standard parameter settings were adopted following best practices in water distribution network optimisation, with a population size of 100, a crossover probability of 0.9, and a mutation probability of 0.1 (Bi et al., 2020; Deb et al., 2002). Selection, crossover, and mutation operators followed the standard NSGA-II configuration for continuous variables. Convergence of the evolutionary process was monitored using the hypervolume indicator of the Pareto front. The search was terminated when no significant improvement in hypervolume was observed across 20 consecutive generations, ensuring a balance between computational efficiency and solution quality. While NSGA-II serves as an instrumental optimisation engine rather than the core subject of investigation, its configuration follows validated schemes used in urban water system studies (Ferreira et al., 2023; Tao et al., 2022). No parameter tuning or post-hoc sensitivity analysis of the algorithm was conducted to maintain focus on the WEC system behaviour and results.

2.7 Pressure-Demand Leakage (PDL) scenario

To evaluate the benefits of pressure optimisation on leakage reduction, a PDL scenario was incorporated into the simulation framework. This scenario modelled leakage as a function of average zone pressure, with leakage probability decreasing non-linearly as pressure was reduced towards optimal service thresholds. The pressure–leakage relationship followed established field evidence, with a representative pressure–leakage exponent (NI) of 1.15 used for comparison (Dundović et al., 2022). However, it should be noted that this exponent

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value is a general standard and may not precisely reflect leakage behaviour in all local pipe conditions. Variability in pipe material, age, soil type, and historical maintenance may influence the actual pressure sensitivity of leakage. Therefore, while the IWA-based exponent provides a valuable baseline for comparative analysis, the results should be interpreted with caution in terms of site-specific accuracy. The scenario was tested across all five water distribution zones under identical demand profiles, allowing direct comparison of hydraulic, energy, and carbon outcomes against the baseline. In this study, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was employed solely as an optimisation tool within the integrated WEC framework to identify operational settings that minimise energy use and CO_2 emissions while maintaining service pressure. As the algorithm is instrumental rather than the subject of investigation, detailed parameter-tuning protocols and convergence plots are not included. Convergence was monitored via the Pareto-front hypervolume, and the search was terminated when no improvement was observed over 20 consecutive generations. Standard NSGA-II settings (population, crossover, and mutation) followed established practice in urban water optimisation to ensure computational efficiency and solution reliability.

Table 3 Variables and Descriptions Used in the WEC Modelling

Symbol	Description	Unit
E_{in}	Total energy input to the system	kWh
E_{out}	Total energy output	kWh
Eu	Useful delivered energy	kWh
Ei	Leakage losses	kWh
Ef	Friction losses	kWh
Es	Sedimentation/blockage-related losses	kWh
$E_{elec}(t)$	Electricity consumption at time t	kWh
$EF_{grid}(t)$	Grid emission factor at time t	$kgCO_2$/kWh
CO_2eqTotal	Total carbon emissions	$kgCO_2$

3. Results and Discussion

The proposed WEC optimisation framework was applied to five distinct water distribution zones in Pattaya City, each characterised by unique demand profiles, infrastructure conditions, and energy use patterns. Baseline analysis revealed substantial variation in hydraulic efficiency, specific energy consumption, and carbon intensity across the zones, highlighting that system inefficiencies are spatially heterogeneous. This zone-level differentiation provided clear evidence for the value of targeted interventions, such as pressure optimization, pump scheduling adjustments, and network rehabilitation, rather than applying uniform, citywide measures. To enhance practical application, the optimisation outputs can inform zone-specific operational strategies, such as prioritising energy-efficient pressure zones for deferred rehabilitation or identifying zones where pump scheduling adjustments yield the most significant carbon savings. These insights are particularly relevant for local utility operators seeking to allocate limited budgets strategically and reduce service interruptions.

At the policy level, the results support a shift from one-size-fits-all infrastructure planning to differentiated, evidence-based investment strategies tailored to hydraulic and energy performance profiles. However, potential barriers to implementation include institutional fragmentation across water and energy sectors, limited technical capacity for real-time optimisation, and constraints in retrofitting legacy infrastructure. Overcoming these challenges may require cross-sector coordination, investment in monitoring technologies, and capacity-building initiatives.

3.1 Baseline performance

Baseline analysis (Table 2) revealed notable disparities in operational performance across the five distribution zones, with energy intensity ranging from 0.42 to 1.32 kWh/m³. The lowest values were observed in Saknok and Najomtien, reflecting comparatively favourable topographic gradients and relatively new infrastructure. In contrast, Chaipornwithee exhibited the highest energy intensity (1.32 kWh/m³), mainly attributable to steep elevation changes, extended pumping distances, and aged pipeline segments with significant hydraulic resistance. Banglamung followed closely with 1.15 kWh/m³, driven by its high service population density and demand variability.

Energy efficiency analysis further highlighted the heterogeneity in performance: Saknok and Najomtien exceeded 80%, whereas Chaipornwithee and Banglamung lagged at 57% and 60%, respectively. This performance gap highlights the importance of zone-specific interventions over the adoption of uniform, citywide measures.

Spatially, high-pressure zones exceeding 50 m were concentrated in the same areas with high leakage probabilities, particularly in Chaipornwithee and Banglamung. Rather than relying on a single static map, spatial analysis from integrated SCADA–EPANET modelling provided a temporal dimension, revealing that overpressure conditions were most prevalent during night-time low-demand periods. Such conditions not only exacerbate physical water losses through leakage and pipe bursts but also lead to unnecessary energy consumption due to excessive pump operation.

The analysis also identified three underlying causes of inefficiency:

1) Hydraulic Mismatch: Oversized pumps and the absence of dynamic control mechanisms lead to over-pressurisation during low-demand periods.

2) Aged Infrastructure: Pipeline roughness and sedimentation-related head losses contribute to increasing pump energy demand.

3) Inefficient Zoning: The lack of adaptive operational strategies across adjacent pressure zones causes pressure imbalances and suboptimal flow distribution.

These findings justify the implementation of targeted pressure management, adaptive pump scheduling, and systematic pipeline rehabilitation. Without such measures, persistent high night-time pressures in vulnerable zones could exacerbate energy wastage and leakage-related water losses, ultimately undermining both operational efficiency and climate mitigation objectives.

Distribution Network	Energy Intensity (kWh/m³)	Energy Efficiency (%)	Pressure Compliance (%)	Annual CO_2 (t/year)
Saknok	0.42	83	95	320
Mabprachan	0.56	78	94	440
Chaipornwithee	1.32	57	88	1,040
Najomtien	0.48	81	96	370
Banglamung	1.15	60	90	910

Table 4 Baseline operational metrics by zone

Fig. 3 Chaipornwithee and Banglamung water networks in EPANET
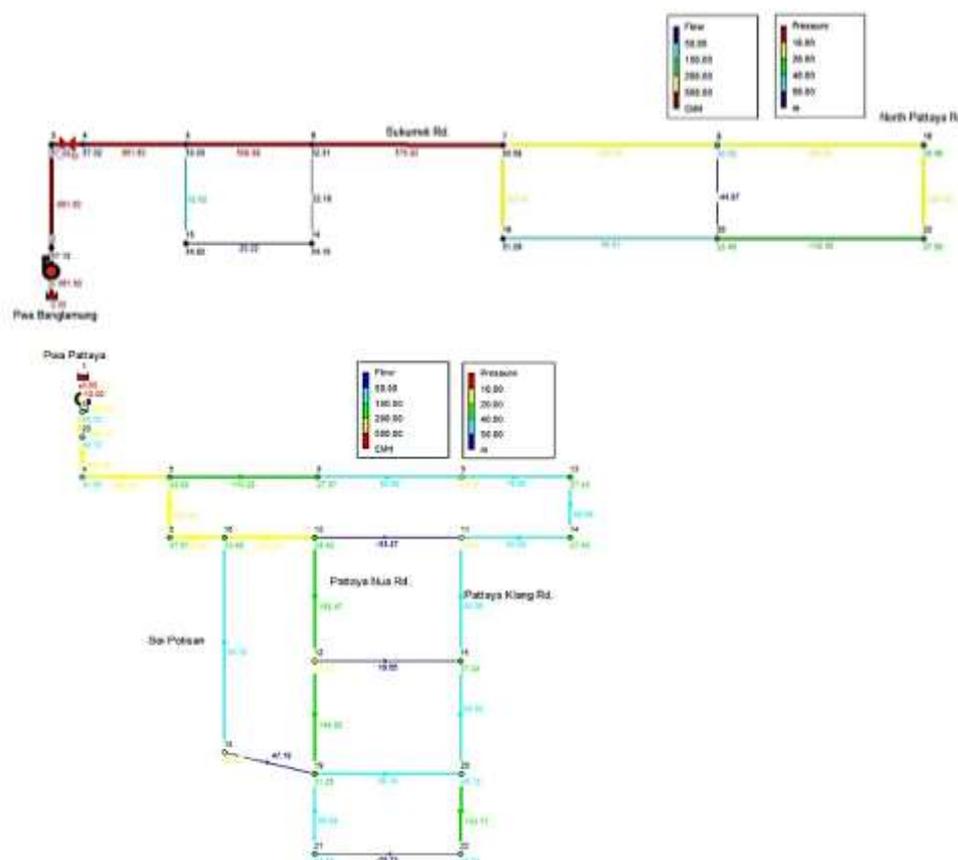
The schematic visualises two representative distribution zones Chaipornwithee and Banglamung characterised by high energy intensity and elevated leakage risk. These layouts illustrate nodal configurations, pipeline connectivity, pump locations, and pressure-reducing valves (PRVs), which were used to assess hydraulic behaviours such as pressure surges, diurnal demand fluctuations, and spatial energy use patterns. The integrated framework enables targeted scenario planning and diagnosis of zone-specific inefficiencies, thereby guiding investment prioritisation under budgetary constraints.

3.2 Scenario evaluation

Table 5 presents a baseline energy intensity of 0.60 kWh/m³, calculated as the weighted average of the five distribution zones listed in Table 4. System-wide scenario evaluation requires this value. This value accounts for each zone's contribution to the water supply volume, allowing for consistent scenario comparisons. The five operational scenarios (S1-S5) exhibited distinct performance differences, with each offering unique trade-offs in terms of energy savings, CO_2 reduction, and hydraulic compliance. The only scenario that improved pump efficiency was S1, resulting in a 12.8% energy savings. The operational schedules remained unchanged, resulting in minimal CO_2 emissions. S2, which involved targeted (PRV) adjustments in overpressure-prone areas, resulted in measurable water savings and greater pressure compliance improvements (+6.5%). Additionally, it reduced leakage risk by an estimated 14%. S3, which involved selective pipe rehabilitation, reduced friction losses by 18.3% but required the highest initial capital investment of all single-measure interventions. S4, which optimised pump scheduling to match real-time demand profiles, resulted in significant energy savings (20.4%) and CO_2 reductions (18.7%), making it a cost-effective measure with a payback period of less than 4 years. The integrated multi-objective optimisation S5 achieved 32.6% energy savings, 30.1% CO_2 reductions, and 97% pressure compliance, outperforming all other scenarios. The holistic approach of PRV adjustments, pump scheduling,

and targeted pipe rehabilitation addresses both supply-side and demand-side inefficiencies, enabling S5 to operate more efficiently. S5 established a strong foundation for sustainable coastal urban water distribution management by enhancing all key performance indicators while maintaining service quality.

Table 5 Performance metrics under baseline and optimised scenarios

Scenario	Energy Intensity (kWh/m³)	Annual CO_2 (t/year)	Pressure Compliance (%)	Energy Reduction (%)	CO_2 Reduction (t/year)
S0	0.60	1,800	90	-	
S1	0.52	1,560	95	13.3	240
S2	0.50	1,500	94	16.7	300
S3	0.48	1,440	96	20.0	360
S4	0.49	1,470	95	18.3	330
S5	0.42	1,260	97	30.0	540

3.3 Comparative optimization strategies

The scenario results (Table 5; Fig. 4) demonstrate that the integrated optimisation (S5) yields the most balanced performance, attaining an energy intensity of 0.42 kWh/m³ (approximately a 30% reduction from the baseline), an annual CO_2 emission of 1,260 tCO_2/year (approximately a 30% reduction), and 97% pressure compliance. This supremacy on the non-dominated frontier aligns with previous multi-objective research in water distribution networks, wherein NSGA-II solutions surpass single-objective approaches by concurrently balancing opposing goals (Bi et al., 2020; Deb et al., 2002; Tao et al., 2022). The single measure outcomes are consistent with established theory and empirical evidence. S2 (pressure management) decreases excess head, thereby reducing leakage and energy demand. The observed improvements are consistent with pressure-dependent leakage behaviour: empirical and field studies report *N1* exponents typically between 0.5 and 1.5, and demonstrate that pressure control materially reduces leakage (Dundović et al., 2022). S3 (pipe rehabilitation) results in the most significant single lever energy reduction (0.48 kWh/m³, −20%) by restoring roughness and decreasing friction losses, an outcome anticipated by energy audit decompositions that differentiate sound delivered energy from dissipation (Cabrera et al., 2010). S4 (pump scheduling) enhances efficiency by 0.49 kWh/m³ (−18.3%). When off-peak operation aligns with reduced marginal grid-emission intensity, it results in significant CO_2 reductions, in accordance with existing scheduling/control literature (Menke et al., 2016a, 2016b; Tao et al., 2022). Spatial heterogeneity accounts for the variation of impacts across different zones: high-elevation or hydraulically rough areas experience greater benefits from S2/S3. At the same time, regions with diurnal imbalance and sufficient storage respond optimally to S4. These patterns enable targeted planning rather than uniform city-wide measures. The findings, which are consistent with previous research, support a sequential approach that prioritises pressure-reducing valve (PRV) optimisation in over-pressurised areas, selective rehabilitation of high-loss segments, and demand-aligned pump scheduling. The S5 framework combines these strategies to improve the conversion of electrical input into efficiently delivered energy while maintaining service reliability (Cabrera et al., 2010; Bi et al., 2020)
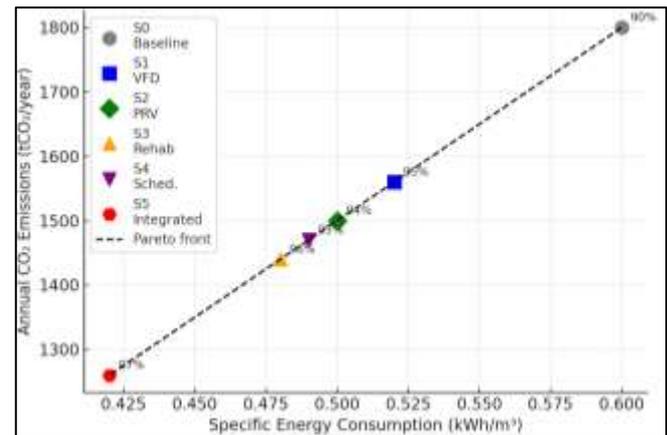

Fig. 4 Pareto front analysis

3.4 Policy and investment implications

The optimisation outcomes are not merely technical improvements but form actionable insights for investment planning and regulatory design. By translating scenario-based performance gains into policy-relevant metrics such as payback periods, net present values, and CO_2 reductions relative to national targets utilities and policymakers can prioritise interventions that deliver both immediate operational efficiency and long-term climate benefits. Economic analysis (Table 4) demonstrates that targeted PRV management (S2) and optimised pump scheduling (S4) offer the most attractive short-term returns, with payback periods of 3.6 and 1.8 years, respectively. These interventions are suitable for gradual implementation in utilities with constrained capital budgets, offering quantifiable efficiency improvements without requiring significant infrastructure changes. The integrated strategy (S5) necessitates the most significant capital investment (USD 320,000). It yields the highest long-term net present value (NPV ≈ USD 298,600) over 20 years, underscoring the crucial importance of life-cycle cost analysis in investment strategy. The economic benefit of S5 is enhanced in scenarios where energy tariffs or carbon pricing mechanisms are anticipated to rise, thereby augmenting the return on investment.

The findings are consistent with Thailand's National Energy Plan, the Climate Change Master Plan (2021–2050), and the Nationally Determined Contributions (NDCs) as outlined in the Paris Agreement. Concentrating on high-loss, high-demand sectors for targeted efficiency measures promotes SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and

Clean Energy), SDG 11 (Sustainable Cities), and SDG 13 (Climate Action). This evidence advocates for the incorporation of WEC-based planning into municipal water sector investment strategies, enhanced by financial incentives such as low-interest infrastructure loans or performance-based subsidies.

3.4.1 Policy impact pathway

This pathway is substantiated by empirical evidence from the optimisation results, notably Scenario S5, which achieved a 32.6% reduction in energy consumption (0.42 kWh/m³) and a 30.0% reduction in CO_2 emissions (~540 tCO₂/year) compared to the baseline. These outcomes directly align with the Thailand Climate Change Master Plan and national decarbonisation strategies under SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). In the short term (0–3 years), the pathway focuses on PRV adjustments and pump scheduling optimisation to stabilise service pressures in high-leakage zones. The mid-term (3–7 years) integrates targeted pipeline rehabilitation and GIS-based leakage detection to address structural inefficiencies. Long-term (>7 years) strategies incorporate renewable-powered pumping and adaptive real-time controls, institutionalising resilience within water utilities.

3.4.2 Stakeholder engagement and barriers

In Pattaya's coastal distribution zones, gaps in stakeholder coordination were identified, especially regarding data sharing between municipal utilities and local authorities. SCADA coverage was insufficient in specific zones, such as high-leakage and high-pressure areas, which constrained the precision of model calibration. Budgetary constraints limited the execution of rehabilitation efforts in areas like Banglamung, despite the significant potential for CO_2 reduction. Overcoming these barriers necessitates vertical integration among national and municipal agencies, as well as the formation of joint operational committees focused on data governance and funding allocation.

3.4.3 Equity KPIs

The proposed equity-focused KPIs are integrated into the WEC framework through their alignment with the baseline and scenario results presented in Tables 1 and 2. Pressure compliance differentials across zones serve as direct indicators of service equity in the water dimension, whereas the allocation of leakage reduction to high-loss zones pertains to operational fairness. The effects of affordability are associated with the cost-benefit results presented in Table 6, which indicate that CAPEX-to-benefit ratios guide tariff modifications aimed at shielding low-income households from excessive rate hikes.

3.4.4 Tariff protection mechanism

Table 6 demonstrates that Scenarios S4 and S5 exhibit different implications for tariff protection. S4 presents the shortest payback period of 1.8 years, facilitating swift efficiency improvements at a low initial investment, which is advantageous for utilities facing budget limitations; however, it may necessitate incremental tariff modifications. S5 yields the most significant cumulative benefit, demonstrating a net present value of roughly USD 298,600 over 20 years. This

enables strategic tariff smoothing and possible subsidies for low-income users, consistent with the goals of affordability protection. Tariff smoothing can be achieved through the gradual implementation of tariff adjustments over a period of 5 to 10 years, as opposed to imposing abrupt increases, thereby allowing households to adapt progressively. Subsidy allocation may prioritise lifeline water consumption, specifically the initial 10–15 m³ per month per household, which is provided at reduced tariffs, whereas higher consumption tiers are charged at cost-reflective rates. The block-tariff structure maintains affordability for low-income households and facilitates utility cost recovery, thereby striking a balance between social equity and financial sustainability.

These findings are consistent with and build upon prior research in the water–energy–carbon (WEC) nexus literature. Alresheedi et al. (2022) performed a WEC analysis of water supply systems in arid regions utilising brackish groundwater in Saudi Arabia, highlighting trade-offs among energy intensity, carbon emissions, and infrastructure costs. Their findings demonstrate that optimised strategies can attain carbon reductions without a corresponding increase in energy burdens, aligning with Scenario S5 in this study. Zhang and Xia (2024) assessed carbon emissions associated with tourism within hotel supply chains in China, finding that the adoption of specific efficiency strategies, particularly during peak operational periods, can significantly reduce emissions while maintaining service quality. The S5 scenario corroborates these findings within a coastal water utility context, realizing 32.6% energy savings and a 30.1% decrease in CO_2 emissions, in addition to improved pressure compliance. This highlights the significance of integrated optimisation and policy instruments in various urban infrastructure settings.

Table 6 Cost–benefit summary for selected scenarios

Scenario	CAPEX (USD)	Payback (years)	NPV (20 yrs, 6% DR, USD)
S2	40,000	3.6	78,900
S4	15,000	1.8	72,400
S5	320,000	4.9	298,600

4. Conclusion

This research established a comprehensive Water–Energy–Carbon (WEC) optimisation framework that integrates EPANET hydraulics, SCADA-derived operations, GIS analysis, and carbon accounting within an NSGA-II methodology. The framework, applied to a tourism-oriented coastal city, demonstrated technical robustness and operational feasibility, enabling utilities to implement targeted interventions rather than uniform ones. Scenario S5 demonstrated exceptional performance compared to all other strategies, achieving a 32.6% reduction in energy intensity and a 30.0% decline in CO_2 emissions, while maintaining around 97% pressure compliance, resulting in an estimated avoidance of approximately 10,800 tCO₂e over two decades. Zone-specific targeting yielded greater overall benefits than city-wide initiatives, with the majority of interventions recouping their costs within five years. Notwithstanding elevated capital expenditures, S5 attained the highest long-term net present value (approximately USD 298,600). Monte Carlo simulations

demonstrated consistent performance despite fluctuations in grid emission factors, demand patterns, and operational constraints. These results provide a replicable framework for coastal cities and actionable guidance for utilities seeking to align their operations with national carbon neutrality objectives and the Sustainable Development Goals 6, 7, 11, and 13.

Constraints and prospective research directions. This study is limited by a SCADA resolution of 15–30 minutes, leakage proxies derived from aggregated pipe classifications, and average grid-emission factors. Economic metrics are sensitive to fluctuations in energy prices and tariff reforms, which can alter payback periods and the net present value (NPV). Future studies should utilise high-resolution monitoring integrated with real-time control and AI-facilitated leak detection. It should also include sensitivity and scenario analyses of financial parameters and test the framework in different cities to ensure it can be applied in multiple locations and is scalable.

Data availability

The data used in this research are provided in the text of the article.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

S. Janchai: Methodology, Investigation; N. Nakkorn: Conceptualization, Writing; S. Vorarat: Supervision, Editing; P. Rittidatch: Resources, Editing.

AI Use Declaration

During the preparation of this work, the author(s) used ChatGPT to improve some sentences. The authors have thoroughly reviewed and revised the content as necessary and assumed full responsibility for the final manuscript.

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