Simulation-based Investigation of Energy Flexibility in the Optimization of Hinterland Drainage

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Abstract. This study investigates the synchronization of pumping operations with dynamic energy prices in hinterland drainage systems. Employing mathematical models and optimization techniques, the research systematically evaluates the inherent flexibility within regular pumping operations. While traditional approaches often focus solely on tidal dynamics to enhance energy efficiency, this study introduces a more comprehensive perspective. Beyond the conventional scope, it incorporates a nuanced analysis of electricity price patterns, aiming to promote grid-friendly behavior and foster an adaptive and efficient response to fluctuating energy availabilities. By delving into these complex interplays, the research not only deepens the understanding of hinterland drainage system dynamics but also proposes an approach for robust and sustainable operational practices. Moreover, the holistic approach aligns with the broader objective of reducing CO2 emissions, reflecting a commitment to environmentally responsible infrastructure management. Through this balanced exploration of operational optimization potentials, the research contributes to the scientific discourse on energy-efficient and environmentally conscious practices in hinterland drainage systems.

Introduction

The ongoing energy turnaround in Germany is changing the way we approach energy-intensive facilities. With the increasing share of renewable energy sources in the power grid, the fluctuation in energy availability naturally rises [1].

These fluctuations directly influence energy prices in the electricity market. Generally, electricity prices tend to be lower when there is a high contribution from renewable sources, and vice versa. In addition to the concept of energy efficiency, there is an additional potential for flexibility. By utilizing this flexibility, operators can reduce energy costs, simultaneously lower indirect CO2 emissions, and relieve the strain on the power grid.

As a result, the cost- and energy-intensive pumping processes in hinterland drainage should be adapted to the significantly more complex conditions in today's electricity market through intelligent control systems. This adaptation aims to ensure holistically optimized drainage strategies. The intensification of rainfall events due to climate change, coupled with the increasing electricity prices, poses challenges for pumping station operators aiming to implement appropriate drainage measures distinct from outdated concepts. In certain cases, relying solely on manual binary decisions and operating pumps at full capacity during high internal or low external water levels may prove insufficient.

By implementing pump speed control, there is the possibility to achieve different efficiencies, with lower speed resulting in significantly reduced energy consumption. However, a longer period is necessary to discharge the same volume of water, and the maximum discharge head that can be overcome is reduced. The choice of the optimal speed depends directly on the current water levels, their rate of change, and the current electricity price at any given time.

To counteract the global increase in CO2 emissions and rising energy costs, extensive knowledge must be generated to understand the complex relationships between controllable factors, such as pump duration and pump speed, and uncontrollable factors like tides, water levels, and weather conditions in a drainage system.

Consequently, a flexible and supply-oriented consumption in energy can be achieved by utilizing forecast data for precipitation, tides, and power availability in the future.

1 State of the Art

The field of energy flexibility is a highly topical issue due to the prevailing energy turnaround, and it is being researched across various industries [2]. In the work by Reinhart et al., energy flexibility is described as the ability of production systems to adapt rapidly and cost-effectively to changes in the energy market [3].

In literature, the inclusion of energy consumption data into classical simulation models for production process planning enables energetic optimizations. By leveraging the temporal flexibility of individual production steps, an optimized adaptation to fluctuations in energy supply or electricity prices can be implemented [4, 5].

Similarly, for applications within the cost- and energy-intesive water management sector, possibilities are being explored to increase energy efficiency of process steps and reduce costs. Mathematical models are typically formulated to represent the mathematical relationship between the in- and outflow of water in a tank or tank cascade. The literature predominantly focuses on water supply or urban drainage [6, 7], with little attention given to drainage systems in coastal regions. However, especially for hinterland drainage, novel methods for drainage optimization arise due to fluctuations in the electricity market. Traditional methods of pumping during low tide are now being contrasted with opportunities for more complex planning of pumping processes that consider the fluctuating electricity price structures [8, 9].

2 Scenario Description

The Kehdingen Maintenance Association (Unterhaltungsverband Kehdingen in German) is one of the 114 associations in Lower Saxony, Germany. Encompassing an area of approximately 27,000 hectares along the Elbe River and its immediate environs, the association is engaged in the operation and management of a comprehensive network comprising approximately 160 pumping stations, housing 400 pumps. The central mandate of this maintenance association revolves around the strategic diversion of water originating from the natural precipitation area.

Given the geographical characteristics of the region, characterized by its low altitude (below sea level) natural drainage becomes a rare occurrence. In instances where natural drainage is unattainable, the accumulated water within the maintenance area necessitates deployment of a considerable energy-intensive mechanism, involving the pumping of water into the surrounding tidal waters. In the past, this process has incurred a substantial annual energy consumption from approximately 2.5 to 3 million kWh, for the maintenance association and its members. Consequently, this energy consumption in the year 2021 corresponded to an average emission output of approximately 1300 tons of CO2 equivalents.

In the context of a conventional drainage system, a diverse array of pumping stations assumes distinct roles, each characterized by specific functions that depend upon its position within the system. Polder pumping stations, for instance, are instrumental in collecting water designated for discharge directly inland, directing it through pump and pipe towards elevated storage basins or canals. Positioned at higher elevations, these storage basins offer two alternative pathways for the water: it can either undergo further elevation through second-stage pumping stations to attain an even greater height, or it can be promptly channeled into neighboring tidal waters by dike pumping stations. The quantity of distinct pumping stations exhibits variability and is tailored to suit the conditions inherent in each locale. Determining factors in this configuration encompass considerations such as the geographical expanse of the area and the overall lift requirement. For instance, there exists a relatively abundant distribution of polder pumping stations situated inland, with second-stage pumping stations strategically deployed on an as-needed basis. In contrast, a comparably limited number of dike pumping stations are strategically positioned at the edges of dikes. In terms of capacity, dike pumping stations inherently have significantly higher capabilities than their counterparts, facilitating the efficient processing of all precipitation water to be discharged from the enclosed area.

Certain pumping stations within the drainage system are equipped with fixed overflow edges, signifying that the water designated for discharge is consistently pumped to an elevated level above the water surface of the subsequent storage basin via an integrated pipe system. The drained water then flows into the next collecting basin. Importantly, the lift height at any given moment is contingent solely upon the prevailing water level within the upstream collecting basin.

Particularly in dike pumping stations, a distinctive operational concept is employed, involving the pumping of water beneath the dike into tidal waters. Notably, the water level within the tidal waters typically exceeds the discharge point of the pump, as illustrated in Figure 1. Consequently, within this concept, the prevailing lift height is dictated by the disparity between the external water level in the tidal waters and the internal water level within the upstream sections.

Given the cyclic variations in tidal water levels, attributed to tidal fluctuations, intervals characterized by relatively high or low lift heights emerge periodically. These fluctuations introduce dynamic variations in the lift heights, accentuating the inherent dynamism associated with the dike pumping station's operational paradigm.

To conduct a comprehensive analysis of specific attributes of the system amid the variability of water levels, a systematic collection of data is undertaken at diverse parameter states crucial to the system's functionality. This process entails the adjustment of the motor speed of the pump, employing a discrete sinusoidal pattern within the operational range under authentic conditions.

This pattern spans the entirety of the operational spectrum, ranging from 65% to 100% of the nominal rotational speed specific to the retailer. The data collection process is facilitated through the implementation of specific measurement systems. These encompass recording of flow rate, power consumption, and water level measurements.

The utilization of these measurement systems ensures capturing an extensive array of system-related data points, contributing to a comprehensive understanding of the system's performance characteristics.

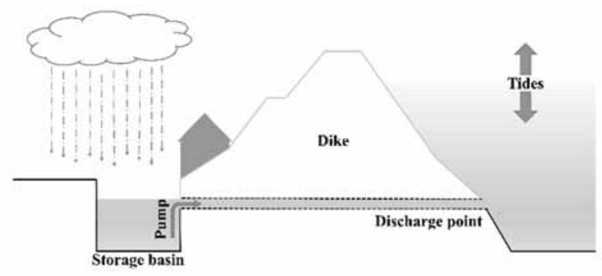

Figure 1: Schematic diagram of a pumping station for pumping rainwater under the dike into tidal waters.

3 Mathematical Model

This section presents the mathematical modeling of a single dike pumping station with a variable-speed pump. Based on this model, different scenarios are compared in terms of a mathematically optimized drainage strategy.

3.1 Model Description

The basis for the subsequent mathematical modeling is the Mixed-Integer Nonlinear Optimization (MINLP) framework presented in the work by Fecarotta et al. [6]. Given that drainage systems typically consist of a network of multi-stage pumps and storage basins exhibiting systematic interdependence, the problem is transformed into a Mixed-Integer Linear Optimization Problem (MILP) using linearization and discretization techniques. This reduction in complexity aims to ensure the calculation of multi-stage pumping schedules within reasonable time constraints under real-world conditions.

Initially, the classification of measured, system-specific data points for the pump results in $N = 7$ equidistant speed ranges (N_1: 65%–70%, N_2: 70%–75%, …). Subsequently, the application of linear regression methods allows the derivation of discretized, linear system characteristic curves.

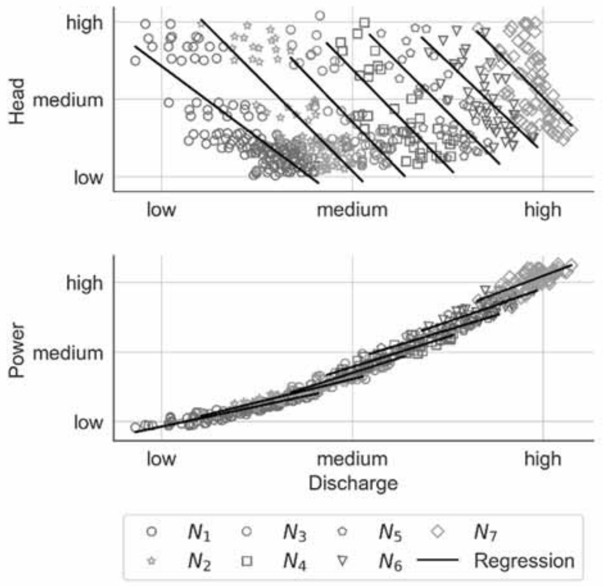

Figure 2: Measured data points with resulting system characteristics of an installed drainage pump in the speed range (N_1 - N_7) from 65 % to 100 % of the specific nominal speed.

These curves define the relationship between head or power and flow rate of the pump, providing insights into the general functioning of a corresponding pump in its operational range (see Figure 2).

Four different vectors are generated to represent the characteristic curves. Vectors M_H and M_P capture the slope of the regression lines for the head and power characteristic curves, respectively. B_H and B_P represent the ordinate interception of the curves.

The mathematical optimization in this work is based on a multicriteria minimization of the sum of the accumulated energy consumption P_t and energy costs K_t with a weighting factor w:

$$\min ZF = \sum_{t\in T} (w \cdot P_\mathrm{t} + \frac{(1-w)}{s} \cdot K_\mathrm{t}) \cdot dt \tag{1}$$

Here, T represents the number of periods, and dt is the duration of the planning periods. Energy costs are derived from the energy consumption and the energy prices p_t of individual periods ($K_t = P_t \cdot p_t$). A scaling factor s adjusts the costs to the range of energy consumption values, with s representing the average value of p_t. The preference for different objective criteria can be varied arbitrarily through the weighting factor w.

The decision variables of the optimization model are represented by binary variables $x_{t,n} \in \{0,1\}$, where $n \in \{0,1,\dots,N\}$ and $x_{t,0} = 1$ signifies the deactivation of the pump in period t. For all $n \in \{1,\dots,N\}$, $x_{t,n}$ represents the choice of one of the N specific speed ranges.

The system is subject to various constraints, which limit the optimization possibilities by restricting the solution space. These constraints are formally presented in the following.

Through a discretized continuity equation

$$H_{\mathrm{in}_t} = H_{\mathrm{in}_{t-1}} + \frac{dQ_{\mathrm{in}_t} - dQ_t}{S} \cdot dt \tag{2}$$

it is ensured that the change in the internal water level H_{in_t} in the reservoir is consistent with the average discharge

$$(dQ_t = \frac{Q_t + Q_{t-1}}{2})$$

and inflow

$$(dQ_{\mathrm{in}_t} = \frac{Q_{\mathrm{in}_t} + Q_{\mathrm{in}_{t-1}}}{2})$$

of water in consecutive time intervals.

These values are based on the discharge Q and inflow Q_in between two consecutive time intervals.

As the water level of the tank should not fall below a certain lower (c_lb) or exceed the upper (c_ub) bound, capacity constraints are defined, which represent an idle and overflow protection:

$$c_\mathrm{lb} \le H_{\mathrm{in}_t} \le c_\mathrm{ub} \tag{3}$$

The head H_t in each time interval is defined as a function of the internal H_{in_t} and external H_{ext_t} water levels:

$$H_t = H_{\mathrm{ext}_t} - H_{\mathrm{in}_t} \tag{4}$$

The following four inequalities allow discrete selection from the N available regression curves for different speed ranges.

By choosing sufficiently high values for H_max and P_max the constraints for non-selected speed ranges $x_{t,n} \, \forall n \in N\backslash\{0\}$ are relaxed to avoid limiting the available solution space.

$$M_{H_n} \cdot Q_t + B_{H_n} - H_\mathrm{max} \cdot (1 - x_{t,n}) \le H_t \tag{5}$$

$$M_{H_n} \cdot Q_t + B_{H_n} + H_\mathrm{max} \cdot (1 - x_{t,n}) \ge H_t \tag{6}$$

$$M_{P_n} \cdot Q_t + B_{P_n} - P_\mathrm{max} \cdot (1 - x_{t,n}) \le P_t \tag{7}$$

$$M_{P_n} \cdot Q_t + B_{P_n} + P_\mathrm{max} \cdot (1 - x_{t,n}) \ge P_t \tag{8}$$

The following two formal relationships ensure that the generatable flow or required power is set to zero if the pump is deactivated. By choosing sufficiently high values for Q_max and P_max the constraints for an active pump are relaxed to avoid restricting its operation in the working area.

$$(1 - x_{t,0}) \cdot Q_\mathrm{max} \ge Q_t \tag{9}$$

$$(1 - x_{t,0}) \cdot P_\mathrm{max} \ge P_t \tag{10}$$

Additionally, it is defined by the following equation that the pump is either deactivated within a time interval ($n = 0$) or exactly one speed range of the pump is activated ($n \in N\backslash\{0\}$).

$$\sum_{n=0}^{N} x_{t,n} = 1 \tag{21}$$

For reasons of plausibility, non-negativity conditions apply to both flow and power:

$$Q_t \geq 0 \tag{32}$$

$$P_t \geq 0 \tag{43}$$

3.2 Experiment Execution

During the execution of the subsequent experiments, various necessary supplementary data values are incorporated into the presented MILP. The Gurobi Solver is utilized to compute an optimal pumping schedule for four consecutive days (or 384 time steps with a time window of 15 minutes).

In addition to implementing three different electricity price patterns (Price 1, 2, and 3) exhibiting varying degrees of electricity price fluctuations (refer to Figure 3), the tidal behavior of a tidal water body is simulated using a sinusoidal function with a 12-hour cycle.

The initial water level of the collecting basin is set to a fixed value, positioned at half the height of the water level suitable for discharge. Furthermore, a linear storage cascade is employed to convert precipitation into runoff data, modeling the inflow to the collecting basin [10]. In this context, an inflow pattern consisting of three randomly consecutive inflows with varying intensity is selected. Additionally, the inflow pattern is scaled by a factor of 1.5 to model a second, stronger inflow, allowing for the examination of different effects.

In Figure 4, an exemplary representation of a single scenario with optimized pump planning over a time horizon of four days is depicted. The first row of the diagram illustrates the underlying electricity price patterns.

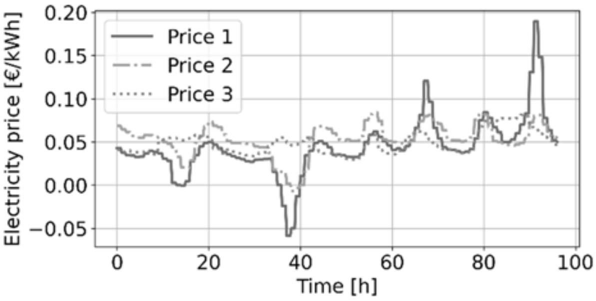

Figure 3: Four-day trends with quarter-hourly resolution of different past wholesale prices for electricity in Germany/Luxembourg based on data from the Federal Network Agency [11].

The second row visualizes the tidal-like behavior of the external water level. Following this is the resulting internal water level of the collecting basin through optimization, starting at the mean of the capacity limits (lower bound: 0.6 m, upper bound: 0.8 m). Row 4 displays the applied inflow pattern, and in the subsequent three rows, the optimal profiles of pump performance data (flow rate, speed, and power) are shown.

Based on the specified conditions, six different study scenarios arise, as presented in Table 1. Each scenario utilizes one of the three electricity price patterns and one of the two inflow intensities.

Within these scenarios, the weighting factor w is varied in equidistant steps between 0 and 1, allowing for the exclusive consideration and optimization of either energy costs or energy consumption, or a weighted combination of both factors.

In order to ensure comparability between the results using different price patterns, a simulation is conducted where the mathematical optimization is applied to 38 cyclic shifts of the inflow pattern.

In each optimization run, the data series is shifted by ten time steps. This shift ensures that different random parameter states occur between current price and inflow, introducing variability.

	Weak inflow	Strong inflow
Price 1	Relatively strong price fluctuations with moderate precipitation	Relatively strong price fluctuations with heavier precipitation
Price 2	Average price fluctuations with moderate precipitation	Average price fluctuations with heavier precipitation
Price 3	Relatively weak price fluctuations with moderate precipitation	Relatively weak price fluctuations with heavier precipitation

Table 1: Presentation of the study scenarios for different electricity price patterns and inflow intesities.

The evaluated metrics include the resulting average energy consumption and average energy costs. The basis for the six scenarios in Table 1 is determined by the optimization results obtained, assuming a constant average price for the underlying electricity price pattern. This assumption serves as a representative benchmark for the respective scenario and is also representative for the optimization of tariff-based electricity procurement.

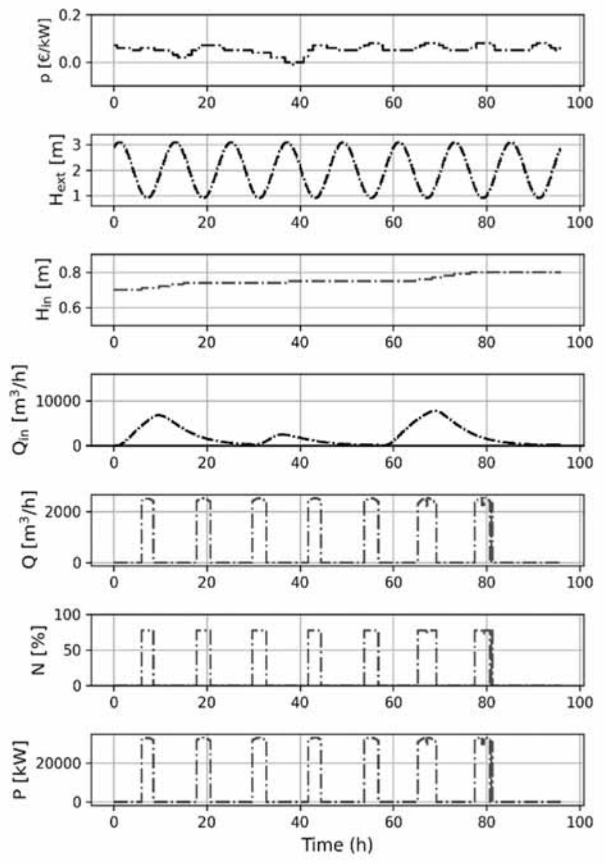

Figure 4: Exemplary optimized pump scenario for four days with fluctuating electricity prices (Price 2) and weak inflow pattern for $w = 1$.

4 Results

The findings presented in Figure 5 illustrate the alteration in the pump pattern corresponding to variations in the weighting factor.

The foundational approach, prioritizing the minimization of energy consumption, defined as $w = 1$, manifests in the planning of requisite pumping operations primarily during phases of relatively low tide. In contrast, it is equally apparent that the strategy of minimizing energy costs with $w = 0$ prompts an adaptation of pumping operations to coincide with periods characterized by lower energy expenses.

Utilizing the data presented in Figure 6, a more in-depth analysis uncovers that, across all scenarios listed in Table 1, the escalation of values for the variable w leads, on average, to a reduction in energy consumption and an increase in energy costs.

Notably, the costs demonstrate a relatively robust exponential growth in this context. Observing from the upper to lower perspective, this effect experiences a swift reduction with decreasing volatility in the electricity price pattern. Similarly, when examining from left to right, the augmentation in inflow intensity mitigates this effect as well.

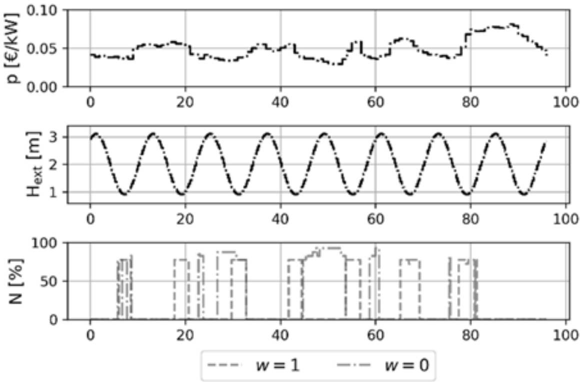

Figure 5: Comparison for the optimization of energy consumption and costs based on exemplarily optimized pump scenarios for four days with a random inflow pattern (Price 3).

Utilizing the data presented in Figure 6, a more in-depth analysis uncovers that, across all scenarios listed in Table 1, the escalation of values for the variable w leads, on average, to a reduction in energy consumption and an increase in energy costs.

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When using constant average prices, $w > 0$ leads to constant average values for energy consumption or energy costs, as the cost optimization criterion offers no advantages due to the absence of electricity price fluctuations. Thus, the resulting energy consumption always corresponds to the consumption for $w = 1$.

However, a different pattern emerges for energy costs. In the presented range, costs at constant electricity price structures exhibit a high negative discrepancy for $w < 1$, as no low-price phases can be utilized for pumping operations.

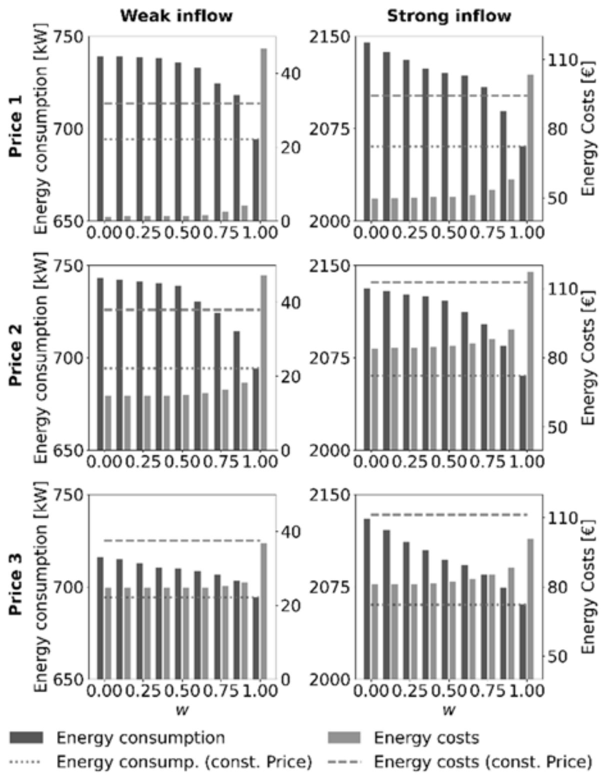

Figure 6: Simulation results for the mathematical optimization of the objective criteria (energy consumption and energy costs) under variation of the weighting factor w for different inflow scenarios and electricity price patterns.

5 Summary

In the context of this research contribution, a simplified Mathematical Model (MILP) was presented, designed to elucidate critical relationships within a drainage system. This model employs complex reduction techniques such as linearization and discretization. The MILP was strategically employed to conduct a comparative analysis of various scenarios, specifically focusing on energy consumption and associated costs.

The study showcased the extent to which costs can be mitigated under specific conditions by integrating considerations of electricity price fluctuations into the strategic planning of pumping operations.

Through extensive simulation efforts, the obtained results were rigorously tested across a diverse range of external conditions.

Notably, our findings underscore the substantial cost-reducing effects achieved through even a modest prioritization of energy costs in the optimization process.

To advance the scope of this research, a promising avenue is the in-depth analysis of multi-stage drainage systems. Furthermore, the exploration of stochastic fluctuations in electricity prices, precipitation, or inflows could yield additional valuable insights.

For example, such an approach could delve into deviations of solution quality from the computed optimum, providing a more comprehensive understanding of the system's dynamic behavior.

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