



A Data-Driven Framework for Identifying the Best Electricity Use Point (BEUP) of a Water Pump Under Real Operating Conditions [†]

Anastasia Papadopoulou ^{1,*} , Vasilis Kanakoudis ², Dimitris Tolikas ², Petros Tsampas ² and Eftychia Papalexiou ³

¹ Civil Engineering Department, University of Thessaly, Pedion Areos, 38221 Volos, Greece

² Civil Engineering Department, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece; kanakoudis@civil.auth.gr (V.K.); dtolikas@gmail.com (D.T.); petros.tsampas@gmail.com (P.T.)

³ Kos Municipal and Sewage Municipal Company, 85300 Kos, Greece; efpapalexiou@gmail.com

* Correspondence: anpapadop@uth.gr

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Abstract

This paper advances pump energy optimization by shifting the analytical focus from nominal efficiency to energy-optimal operating areas derived directly from in-field measurements. A structured experimental methodology is presented for reconstructing pump performance under real hydraulic and electrical conditions using existing systems and variable frequency drives. High-resolution datasets obtained from in-field testing are densified and normalized to map the operational area of pumps across flow, head, and rotational speed. The Best Electricity Use Point (BEUP) is identified as an energy-optimal area rather than a single operating point, accounting for system-level losses. Application to a municipal water supply pumping station on Kos Island (Greece) demonstrates that real operating behavior deviates substantially from manufacturer specifications and that BEUP-oriented control enables systematic reductions in energy consumption while improving hydraulic stability and mechanical stress conditions. The proposed framework supports a transition from static efficiency concepts to adaptive, measurement-driven pump operation.

Keywords: pump characteristic curves; energy efficiency; in-field experimentation; variable speed operation; water supply systems

1. Introduction

Pumping systems account for a significant share of energy use in water infrastructure, reaching about 4% of total electricity consumption in the United States [1]. Urban systems exhibit an average energy intensity of ~ 1 kWh/m³, or ~ 100 kWh per capita annually [2]. Energy demand is driven by factors such as topography, elevation, pump characteristics, and control strategies. Over time, mechanical wear degrades pump performance, leading to an estimated $\sim 1\%$ annual increase in energy consumption and a non-linear decline in hydraulic efficiency [3].

In Greece, energy efficiency in water systems is a strategic priority under the National Energy and Climate Plan (NECP) [4]. The sector includes 126 municipal water utilities and major utilities such as EYDAP S.A. and EYATH S.A., with total consumption exceeding 1700 GWh/year (Table 1). The high energy intensity of water supply systems, combined with national energy dependency and electricity price volatility, increases the sensitivity of



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operational expenditure to pumping efficiency. Therefore, the implementation of advanced control and optimization strategies in pumping stations constitutes a critical pathway for improving energy performance and ensuring long-term operational sustainability.

Table 1. Greek water sector–energy profile.

Indicator	Value
Total sector energy use	~1700 GWh/year
Share of national electricity	~3.2%
Share of pumping in energy use	~75%
Energy cost share (OPEX)	25–30% (up to 45%)
Average water losses	~25% (up to >50%)

Despite the clear impact of pumping on both energy consumption and costs, systematic performance monitoring and optimization remain limited. This creates a critical gap between available data and operational decision making. The BEUP addresses this gap through an optimization-based Decision Support System (DSS) for pump operation. The approach integrates real-time data, pump characteristics, and operational constraints, incorporating parameters such as variable speed drives, demand variability, energy pricing, pressure management, and network dynamics (Table 2).

Table 2. BEUP conceptual framework.

Component	Description
Data integration	SCADA, telemetry, pump curves
Core function	Energy optimization of pumping
Key variables	Demand, pressure, pricing, scheduling
Output	Operational recommendations (DSS)
Scope	Site-specific, scalable across utilities

This structured, data-driven approach enables improved energy efficiency, reduced operational costs, and enhanced sustainability of water distribution systems.

2. Theoretical Framework of Pump Operation and Energy Optimization

2.1. Pump Characteristic Curves

Pumps in water supply systems are selected based on key hydraulic requirements, primarily flow rate (Q) and head (H). Their performance is defined by characteristic curves provided by manufacturers at a constant rotational speed (ν), including the flow–head (Q – H), flow–efficiency (Q – η), and flow–power (Q – P) relationships. These curves form the basis for evaluating pump behavior under varying operating conditions. The Q – H curve typically exhibits a decreasing trend of head with increasing flow, reflecting stable hydraulic operation. The Q – P curve indicates increasing power demand as flow rises, while the Q – η curve identifies the Best Efficiency Point (BEP), corresponding to maximum hydraulic efficiency. However, the BEP does not account for total electrical energy consumption. To address this limitation, the concept of the Best Electricity Use Point (BEUP) is introduced. BEUP represents the operating condition that minimizes electrical energy consumption per unit volume of water delivered, thus providing a more comprehensive and economically relevant optimization criterion compared to BEP.

2.2. Speed Variation and Efficiency Adjustment

Pump characteristic curves are valid for a specific rotational speed (v_1) but can be transformed for a different speed (v_2) using the affinity laws:

$$Q \propto \frac{v_2}{v_1}, H \propto \left(\frac{v_2}{v_1}\right)^2, P \propto \left(\frac{v_2}{v_1}\right)^3 \quad (1)$$

where Q is the flow rate (m^3/h), H is the pump head (m), P is the absorbed power (kW), and v_1, v_2 are the initial and modified rotational speeds (rpm), respectively.

These relationships enable the prediction of pump performance under variable speed operation. Although classical theory assumes that efficiency remains independent of rotational speed, empirical studies [5] demonstrate that efficiency is affected by speed variations. Furthermore, long-term operation leads to performance degradation due to mechanical wear (e.g., impeller erosion, bearing losses, internal leakages), necessitating periodic recalibration of characteristic curves [3].

The BEP corresponds to the maximum ratio of hydraulic power to shaft power, representing minimum internal losses. However, it excludes motor and electrical losses, resulting in an incomplete representation of total system efficiency. In contrast, BEUP incorporates the full energy chain, including electromechanical losses, and therefore reflects the true energy-optimal operating condition.

Accurate, up-to-date pump characteristic curves are thus essential for intelligent energy management. The BEUP approach builds on this principle by integrating real-time data acquisition, in-field experimental recalibration, and adaptive control of rotational speed. This enables continuous operation near BEUP, ensuring optimal performance from both hydraulic and electrical perspectives.

3. Methodological Approach

3.1. BEUP Approach for Determining the Best Electricity Use Point (BEUP)

The proposed BEUP methodology is designed to identify the energy-optimal operating conditions of pumping systems with minimal disruption to normal utility operations. It leverages existing infrastructure, including SCADA systems and variable frequency drives (VFDs), to enable real-time acquisition of hydraulic and electrical parameters and dynamic control of pump rotational speed. At the core of the approach lies the functional relationship $v = B(Q)$, which defines the optimal rotational speed as a function of flow rate. This relationship is derived through stepwise multivariate regression, aiming to minimize electrical power consumption under varying operational conditions.

The methodology is based on in-field experimental testing, during which pump characteristic curves ($Q-H$, $Q-\eta$, $Q-P$) are redefined across multiple rotational speeds. Unlike conventional approaches focused on the Best Efficiency Point (BEP), the BEUP introduces the Best Electricity Use Point (BEUP), defined as the operating condition that minimizes total electrical energy input per unit of delivered water. BEUP explicitly incorporates motor, inverter, and auxiliary losses, providing a more representative optimization target aligned with real operational costs.

3.2. Rationale for BEUP-Based Optimization

The BEUP concept extends beyond traditional hydraulic efficiency metrics. While the BEP is defined based on shaft power and excludes electrical losses, the BEUP directly reflects actual energy expenditure as measured by SCADA systems. This distinction is critical in real-world systems, where motor performance, drive efficiency, and equipment aging significantly influence overall energy consumption. The BEUP framework enables

rapid in situ identification of optimal operating conditions, realistic assessment of pump performance and degradation, and improved decision making for maintenance and replacement strategies. Consequently, BEUP provides a more robust and economically relevant criterion for pump operation in modern water utilities.

3.3. Integrated Optimization Methodology

To move beyond discrete experimental measurements, BEUP implements a computational framework that combines data-driven characterization with optimization. The methodology consists of three main stages:

1. **Data Densification and Normalization.** Experimental measurements are expanded to cover the full operational domain (Q–H space) through interpolation techniques.
2. **Construction of a Computational Grid.** A structured Q–H grid is generated, where each node is associated with flow rate (Q), head (H), rotational speed (v), and efficiency (η).
3. **Optimization and Control.** Pump operation is optimized by adjusting rotational speed via inverters to maintain operation within high-efficiency regions and satisfy system-level hydraulic constraints, typically expressed through a parabolic energy relationship.

This integrated approach enables continuous, data-driven optimization of pumping systems under real operating conditions.

3.4. Data Densification and Interpolation

Following experimental data acquisition, the BEUP applies a densification process to transform discrete measurements into a continuous representation of pump performance. A uniform grid is defined over the operational domain using increments ΔQ and ΔH . Interpolation is performed using triangular elements formed between successive characteristic curves. For any point within the grid, performance variables (e.g., efficiency or rotational speed) are computed using weighted interpolation:

$$Z(x, y) = aZ_1 + bZ_2 + cZ_3 \quad (2)$$

where Z_1 , Z_2 , Z_3 are the values at the triangle vertices and a , b , and c are interpolation weights.

This process enables rapid estimation of optimal operating conditions across the full range of system states, bridging the gap between field measurements and real-time control.

3.5. System Integration and Operational Deployment

The processed datasets are stored in structured databases (e.g., SQL), enabling efficient retrieval during operation. The BEUP platform, implemented using modern software architectures (Java/Spring Boot), supports automated data processing and real-time decision making. To facilitate practical use, the operational domain is segmented into efficiency zones (e.g., high, acceptable, low). This classification supports rapid identification of cost-optimal operating strategies, particularly when combined with system-level constraints such as reservoir dynamics and demand variability.

3.6. Optimization of Multi-Pump Systems

For pumping stations operating multiple pumps in parallel, BEUP extends the optimization framework to determine system-wide efficiency. The hydraulic behavior of the system is described by a parabolic energy curve:

$$H = a + bQ^2 \quad (3)$$

At each operating point, multiple combinations of individual pump flows (Q_1, Q_2) can satisfy the total demand:

$$Q = Q_1 + Q_2, H = H_1 = H_2 \quad (4)$$

For each combination, total efficiency is evaluated based on hydraulic output and electrical input. The optimal configuration is identified by maximizing system efficiency (or equivalently minimizing energy consumption).

The procedure involves:

- evaluating all feasible combinations of pump operating points,
- determining local efficiency maxima along the system curve,
- identifying the global optimum corresponding to minimum energy use.

This framework can be generalized to systems with multiple pumps and varying operational constraints.

4. Case Study on the Kos Island

4.1. Study Area and Data Requirements

The proposed methodology was applied to the Ydatopyrgos (Water Tower) pumping station of the Kos urban freshwater network in Greece to evaluate pump performance under real operating conditions and assess the applicability of the BEUP optimization framework. The case study focused on the acquisition of field data required for reconstructing pump characteristic curves and estimating potential energy savings. The monitored variables included pressure, tank level, flow rate, electrical power, and pump rotational speed, together with key geometric and hydraulic characteristics of the pumping station and discharge system [6].

4.2. Energy Savings Assessment Framework

Under actual operating conditions, both flow rate and hydraulic head vary continuously due to tank level fluctuations, variable demand, and changes in pump configuration. In conventional operation, pumps typically run at fixed speed and therefore rarely operate exactly at their energy-optimal point. As a result, energy consumption remains suboptimal. In contrast, the BEUP approach uses SCADA data and inverter-based speed control to maintain pump operation at or near the Best Electricity Use Point (BEUP), thereby reducing electrical losses and improving overall efficiency.

To estimate the potential benefit, two operational modes are compared conceptually:

- (a) conventional fixed-speed operation, and
- (b) variable speed operation controlled to track the BEUP.

For the case study of the Kos Island reservoir filling, the total energy demand is expressed by integrating the ratio P/Q over the water level rise from h_0 to h_1 . The difference between the two operating modes provides the estimated percentage energy saving. Although the filling times differ between the two cases, the same final storage level is reached, allowing a direct comparison of energy performance.

4.3. Pumping Station Configuration and Experimental Setup

The experimental procedure was conducted at the Ydatopyrgos pumping station on 23 November 2024 for pump M01 and on 24 November 2024 for pump M02, with additional tests under parallel operation of both pumps. The two pumps were of the same type (92SV02G150T/D) and were connected to metallic storage reservoirs via a DN200 suction pipe. Water was discharged through a DN200 collector toward an elevated water tower approximately 20 m high. The suction line length was about 20 m, while the discharge sys-

tem extended approximately 40 m in total, including both horizontal and vertical sections. Field-derived curves at 50 Hz differed from the manufacturer's nominal curves, indicating the influence of wear, hydraulic constraints, or other site-specific operating conditions.

The site presented important measurement limitations. No pressure sensor was installed at the suction side, and no dedicated discharge side pressure sensor or inline flow meter was available along the discharge pipeline. In addition, the pumps operated alternately, and pump M01 was located closer to the inlet/outlet piping. These constraints required indirect estimation of total pump head during data processing.

The field test protocol was designed to minimize disruption to normal operation. For each valve position, testing began with the butterfly valve fully open at 50 Hz. Pump frequency was then gradually reduced in small increments, with stabilization pauses every 0.5 Hz, until the minimum allowable flow rate was reached. The valve position was then adjusted to a new throttling condition and the procedure was repeated. This sequence generated a broad dataset of flow pressure–frequency combinations over the feasible operating range. Outliers in the raw flow measurements were removed during preprocessing, and testing was interrupted whenever the tank level approached overflow.

The BEUP methodology was applied at the Ydatopyrgos pumping station (Kos). Following data densification and normalization, an SQL dataset (InputAI) was constructed, containing all variables required for determining the Best Electricity Use Point (BEUP) of the system. For each hydraulic head value ($H = 22.4\text{--}38.8\text{ m}$, $\Delta H = 0.2\text{ m}$) and for each pair of pump flow rates (Q_1, Q_2), the dataset includes frequency (F_1, F_2), electrical power (P_1, P_2), pump efficiencies (η_1, η_2), and total system efficiency (η).

The flow combinations satisfy the system energy equation:

$$H = a + b(Q_1 + Q_2)^2. \quad (5)$$

where $a = 20.62\text{ m}$ (static head) and $b = 6.0442 \times 10^{-4}\text{ s}^2 \cdot \text{m}^{-5}$ (head losses), reflecting parallel pump operation ($H = H_1 = H_2$, $Q = Q_1 + Q_2$).

Based on this dataset, the BEUP calculates the operating conditions that minimize total electrical consumption for a given hydraulic requirement. The BEUP is therefore not a single point but a set of operating states (frequency–flow combinations) that ensure minimum energy use under varying system conditions.

4.4. Single-Pump Operation

Operating points derived from the intersection of pump characteristic curves with the system curve indicate clear deviations from manufacturer specifications, confirming performance degradation due to long-term operation (Table 3).

Table 3. Energy consumption comparison for single-pump operation (reference volume: 1000 m^3).

Case	H (m)	Q (m^3/h)	P (kW)	t (h)	Energy (kWh)	Δ (%)
Manufacturer (nominal)	29.4	120.1	14.4	8.3	119.9	25.6
Pump 1 (field)	27.2	104.8	13.3	9.5	126.9	33.0
Pump 2 (field)	26.5	98.0	12.5	10.2	127.6	33.7
BEUP	23.4	67.8	6.47	14.7	95.4	0.0

- New pump: $Q = 120.1\text{ m}^3/\text{h}$, $H = 29.4\text{ m}$, $P = 14.4\text{ kW}$
- Pump 1: $Q = 104.8\text{ m}^3/\text{h}$, $H = 27.2\text{ m}$, $P = 13.3\text{ kW}$
- Pump 2: $Q = 98.0\text{ m}^3/\text{h}$, $H = 26.5\text{ m}$, $P = 12.5\text{ kW}$

The results indicate an efficiency degradation of approximately 5–6% relative to nominal conditions. However, operation at BEUP leads to a significant reduction in

energy consumption (~25.6%), despite lower flow rates, due to improved overall electrical efficiency (Figure 1).

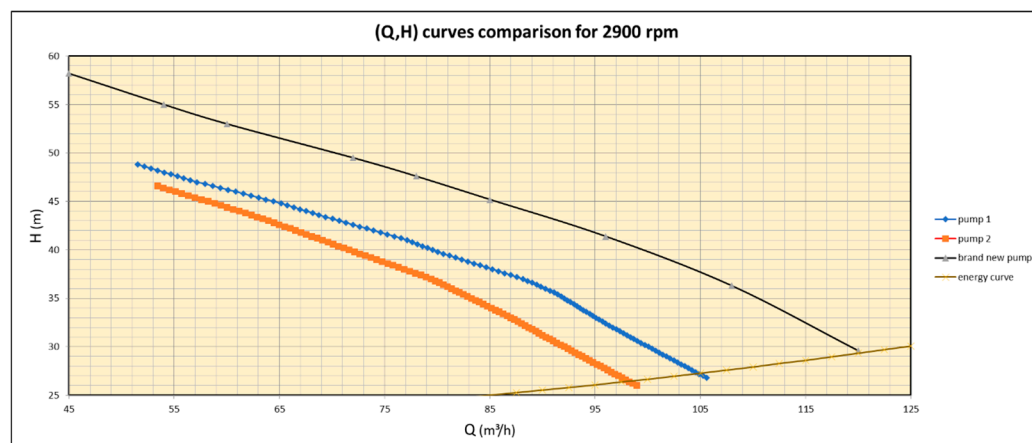


Figure 1. Comparison between field-derived Q–H curves of Pumps 1 and 2 (Single-Pump Operation) and the nominal manufacturer curve.

4.5. Parallel-Pump Operation

The analysis was extended to the simultaneous operation of both pumps operating in parallel (Table 4).

Table 4. Energy consumption comparison for parallel operation (reference volume: 1000 m³).

Case	H (m)	Q (m ³ /h)	P (kW)	t (h)	Energy (kWh)	Δ (%)
Manufacturer ×2 (nominal)	42.0	188.2	27.2	5.3	144.7	25.6
Pumps 1 & 2 (field)	37.2	166.5	24.9	6.0	149.5	0.0
BEUP	37.6	157.6	25.1	6.0	149.5	0.0

Under parallel operation, the total energy consumption at the BEUP is comparable to that under conventional operation. This indicates that, in this specific hydraulic regime, the primary benefit of the BEUP lies in operational stabilization and correct pump allocation, rather than additional energy savings (Figure 2).

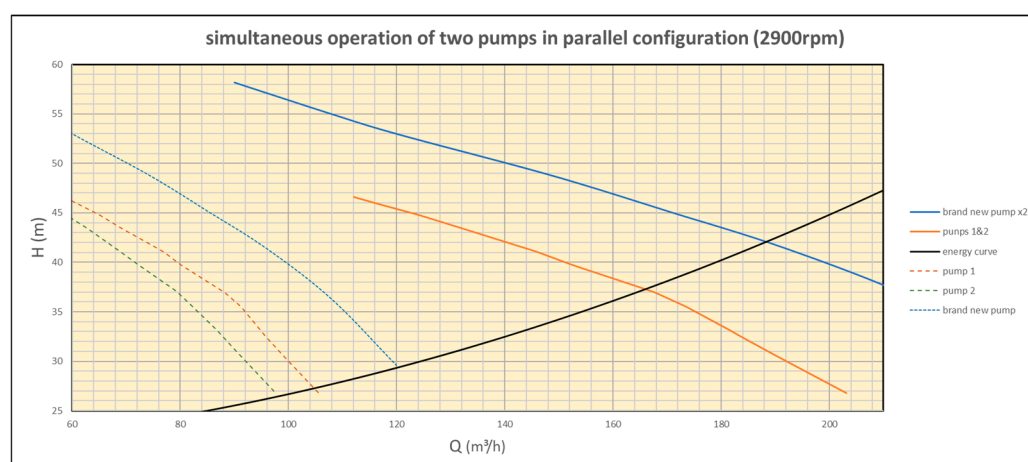


Figure 2. Comparison between field-derived Q–H curves of Pumps 1 and 2 (Parallel-Pump Operation) and the nominal manufacturer curve.

4.6. Interpretation in the Context of BEUP

The results confirm that the BEUP concept provides a more realistic optimization framework than the conventional Best Efficiency Point (BEP), as it accounts for the entire electrical energy chain, including motor and inverter losses. The analysis demonstrates that pump aging leads to measurable deviations from nominal performance curves, while BEUP-based control significantly improves efficiency, particularly under single-pump operation. The optimal operating configuration—single or parallel—depends on the required flow rate and the system curve, indicating that energy optimization must be evaluated at the system level. Under parallel operation, the BEUP primarily ensures appropriate load distribution between pumps rather than substantial additional energy savings, as evidenced by the comparable energy consumption observed between the BEUP- and field-based parallel operation (149.5 kWh), while nominal operation of two pumps results in slightly lower energy demand (144.7 kWh, −3.3%) (Table 5).

Table 5. Energy consumption comparison for parallel pump operation (reference volume: 1000 m³).

Case	H (m)	Q (m ³ /h)	P (kW)	t (h)	Energy (kWh)	Δ (%)
Manufacturer (nominal)	42.0	94.1	13.6	—	—	—
Pump 1 (field)	37.2	87.6	12.8	—	—	—
Pump 2 (field)	37.2	78.9	12.1	—	—	—
Manufacturer × 2 (nominal)	42.0	188.2	27.2	5.3	144.7	−3.3
Pumps 1 & 2 (field)	37.2	166.5	24.9	6.0	149.5	0.0
BEUP	37.6	167.6	25.1	6.0	149.5	0.0

Notes: Δ (%) expresses additional energy consumption relative to BEUP operation. Time (t) corresponds to the duration required to pump 1000 m³. “—” indicates values not directly comparable under the same reference volume.

Overall, the methodology enables continuous adaptation of pump operation to dynamically varying hydraulic conditions. Consequently, the BEUP approach demonstrates that energy optimization in real systems is inherently multi-parameter and system-dependent, requiring adaptive control strategies rather than reliance on fixed design points.

5. Conclusions

This study presents a comprehensive framework for energy optimization in water supply pumping systems, combining in-field experimentation, data-driven modeling, and real-time operational control. The proposed methodology is based on the Best Electricity Use Point (BEUP), which extends conventional performance assessment by incorporating total electrical energy consumption.

The experimental application in the Kos water supply system revealed systematic deviations between actual and manufacturer-defined pump characteristic curves, attributable to aging, operational conditions, and system constraints. The in-field protocol enabled reconstruction of performance curves under real conditions and identification of energy-optimal operating regions. The results show that BEUP-based variable speed operation reduces energy consumption by approximately 3–5% under single-pump operation, with higher savings potential under optimized parallel configurations. Additionally, the analysis confirms that optimal performance is not associated with a single operating point but with a dynamic operating region, requiring continuous adjustment of pump speed.

From an operational perspective, the results demonstrate that BEUP-based control directly improves the key performance indicator energy intensity (kWh/m³), which is widely used for benchmarking pumping station efficiency. The observed energy savings translate into lower kWh per unit volume delivered, even when operating at reduced flow rates, due to improved overall electrical efficiency.

The findings further indicate that system-level optimization (pump combinations and frequency control) is required to minimize kWh/m³, particularly under variable demand conditions. This shifts operational practice from static, fixed-speed control toward adaptive, demand-driven operation, enabling utilities to:

- reduce energy costs,
- improve asset utilization,
- enhance operational reliability.

The methodology provides a directly implementable framework within SCADA environments, supporting real-time decision making based on measurable performance indicators.

From a scientific standpoint, the study demonstrates that pump efficiency is not invariant and deviates from nominal performance due to aging and system interaction effects, challenging conventional assumptions embedded in standard pump theory.

The introduction of BEUP establishes a system-based optimization criterion that integrates hydraulic and electrical efficiency, moving beyond the traditional BEP concept, which considers only hydraulic performance. The results further show that energy optimization is inherently multi-parameter and system-dependent and cannot be adequately described by fixed design points. Moreover, the identification of a dynamic optimal operating region, rather than a single optimal point, provides a conceptual advancement for pump operation modeling and supports the development of adaptive, data-driven control strategies. The implementation highlighted practical constraints, including measurement limitations (e.g., absence of suction pressure data) and the need for controlled testing conditions. These factors introduce uncertainty in performance estimation and underline the importance of enhanced measurement equipment.

Future work should focus on long-term validation using kWh/m³ as a primary KPI, large-scale deployment across multiple pumping stations, and integration with predictive analytics to further improve robustness and scalability.

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