UDK: 535.33:378.147

THEORETICAL FOUNDATIONS OF ENERGY EFFICIENCY IN THE APPLICATION OF TECHNOLOGICAL PROCESSES AT WATER RESERVOIRS

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https://doi.org/10.5281/zenodo.22908784

ABSTRACT

Energy efficiency plays a critical role in the sustainable management of water reservoirs, which are essential for agricultural irrigation, municipal water supply, and hydroelectric power generation. This article explores the theoretical, scientific, and practical foundations of optimizing energy consumption in core technological processes within reservoir systems, including high-capacity pumping, sediment management, water level regulation, and automated SCADA monitoring.

The study evaluates the integration of conventional power with renewable energy sources (RES)—specifically floating photovoltaic (FPV) systems, micro-hydroturbines, and wind energy. Mathematical models of energy balance and efficiency coefficients (η) are analyzed to identify technical and hydraulic energy losses. The findings indicate that implementing hybrid renewable energy systems not only mitigates grid dependency and operational costs, but floating solar panels also reduce water evaporation while gaining a 5-12\% efficiency boost due to water-cooling effects. Furthermore, incorporating Variable Frequency Drives (VFDs) into pumping infrastructure reduces overall energy consumption by 20-30%

This research offers a comprehensive theoretical framework for water-energy nexus optimization, providing actionable insights for engineers and policymakers aiming to enhance the operational reliability, economic viability, and environmental sustainability of modern water infrastructure.

Keywords: Water reservoirs, technological processes, energy efficiency, renewable energy, floating solar panels, pumping stations, SCADA systems, water-energy nexus.

ANNOTATSIYA

Energiya samaradorligi qishloq xo‘jaligini sug‘orish, aholini ichimlik suvi bilan ta’minlash va gidroenergetika uchun o‘ta muhim bo‘lgan suv omborlarini barqaror boshqarishda hal qiluvchi rol o‘ynaydi. Ushbu maqolada suv ombori tizimlaridagi asosiy texnologik jarayonlar — yuqori quvvatli nasoslar vositasida suvni haydash, cho‘kindilarni tozalash, suv sathini tartibga solish va avtomatlashtirilgan SCADA monitoringida energiya sarfini optimallashtirishning nazariy, ilmiy va amaliy asoslari tadqiq etiladi.

Tadqiqotda an’anaviy energiya tizimlarini muqobil energiya manbalari (QTEM) — xususan, suzuvchi quyosh panellari (FPV), mikro-gidroturbinalar va shamol energiyasi bilan integratsiya qilish imkoniyatlari baholanadi. Texnik va gidravlik energiya yo‘qotishlarini aniqlash uchun energetik balans va foydali ish koeffitsiyenti (η)matematik modellari tahlil qilingan. Natijalar shuni ko‘rsatadiki, gibrid QTEM tizimlarini joriy etish elektr tarmog‘iga qaramlikni va ekspluatatsiya xarajatlarini kamaytiradi, shuningdek, suzuvchi quyosh panellari suvning bug‘lanishini pasaytirib, suvli sovutish effekti hisobiga o‘z FIKini 5–12% ga oshiradi. Bundan tashqari, nasos infratuzilmasiga chastotali o‘zgartirgichlarni (VFD) tatbiq etish umumiy energiya sarfini 20–30% ga tejash imkonini beradi.

Ushbu tadqiqot zamonaviy suv xo‘jaligi infratuzilmasining operatsion ishonchliligi, iqtisodiy samaradorligi va ekologik barqarorligini oshirishni maqsad qilgan muhandislar va qaror qabul qiluvchi mutassislar uchun suv-energetika bog‘liqligini (water-energy nexus) optimallashtirish bo‘yicha yaxlit nazariy bazani taqdim etadi.

Kalit so‘zlar: Suv omborlari, texnologik jarayonlar, energiya samaradorligi, qayta tiklanuvchi energiya, suzuvchi quyosh panellari, nasos stansiyalari, SCADA tizimlari, suv-energetika bog‘liqligi.

Introduction

Water reservoirs serve as cornerstone infrastructure in global water-energy-food security, playing an indispensable role in agricultural irrigation, municipal supply, flood control, and hydroelectricity generation. However, managing these complex systems involves continuous, high-intensity operational activities. Key technological processes—such as high-capacity water lifting, gate actuation, sediment control, and real-time supervisory control and data acquisition (SCADA) monitoring—require significant amounts of electrical energy. In an era marked by accelerating climate change, global energy volatility, and increasing water scarcity, minimizing the energy intensity of these operations is no longer merely an economic goal, but a strategic necessity.

Historically, water management facilities have relied almost exclusively on centralized electrical grids, exposing operations to tariff fluctuations and transmission inefficiencies. Furthermore, inefficient hydraulic dynamics and outdated pumping technology often result in substantial energy losses. To address these vulnerabilities, the paradigm of the "water-energy nexus" has emerged, emphasizing the intrinsic interdependence between energy systems and water infrastructure. Optimizing this relationship requires transitioning from conventional, single-source power models toward integrated, decentralized energy frameworks.

The integration of renewable energy sources (RES) directly into reservoir environments offers a promising pathway toward sustainability. Technologies such as floating photovoltaic (FPV) systems, micro-hydroturbines installed at discharge outlets, and local wind turbines present distinct advantages. FPV systems, in particular, maximize spatial efficiency by utilizing unused water surfaces while simultaneously mitigating evaporation losses and achieving higher electrical yields due to the cooling effect of the water body. Complementing these renewable generation assets with variable frequency drives (VFDs) and smart grid automation creates a resilient operational ecosystem capable of dynamic load balancing and peak-shaving.Despite these technological advancements, establishing a clear theoretical foundation for evaluating energy efficiency across diverse reservoir operations remains a critical gap. Comprehensive models that accurately combine energy balance principles, hydraulic losses, and the variable nature of renewable generation are essential for optimal system design.This paper establishes the theoretical, scientific, and practical foundations for enhancing energy efficiency in water reservoir operations. By formulating mathematical models for energy balance, evaluating the theoretical synergies of RES integration, and outlining key performance indicators, this research provides a strategic framework to guide engineers, facility managers, and policymakers toward sustainable, resource-efficient water infrastructure management.

Methods:

To establish the theoretical foundations and assess the efficiency of energy source integration within water reservoir operations, this study employs an integrated methodological approach combining mathematical modeling, thermodynamic energy balance analysis, and empirical data validation.

2.1. Energy Balance and Efficiency Modeling

The total theoretical energy efficiency (η_{sys}) of the technological processes within a reservoir system—primarily focusing on high-capacity pumping operations—is modeled using the law of conservation of energy:

$$\eta_{sys} = \eta_m \times \eta_p \times \eta_h \times \eta_t$$

Where: η_m = Electric motor efficiency; η_p = Mechanical pump efficiency; η_h = Hydraulic efficiency of

piping/intake; η_t = Electrical transmission & transformer efficiency.
The total useful hydraulic power (P_{useful}) required to lift a volume of water is defined as:

$$P_{useful} = (\rho \times g \times Q \times H) / (3600 \times 1000) \text{ [kW]}$$

Where: ρ = water density (kg/m³), g = gravitational acceleration (9.81 m/s²), Q = volumetric flow rate (m³/h), H
= total dynamic head (m).

2.2. Modeling Renewable Energy Integration
a) Floating Photovoltaic (FPV) Output Model:
The thermal regulation effect of the water body on PV panel performance is integrated into the power output equation:

$$P_{FPV} = Y_{PV} \times f_{PV} \times (G_T / G_{STC}) \times [1 + \alpha_p \times (T_c - T_{STC})]$$

Where: Y_{PV} = rated capacity under STC (kW), f_{PV} = PV derating factor, G_T = solar irradiance (W/m²), α_p
= temperature coefficient (%/°C), T_c = cell temp under water-cooling (°C).
b) Micro-Hydrokinetic Energy Harvesting:
Energy recovery from continuous discharge structures (outlets and spillways) is computed using:

$$P_{hydro} = \rho \times g \times Q_{disc} \times H_{net} \times \eta_{turbine}$$

Where: Q_{disc} = irrigation/discharge flow rate (m³/s), H_{net} = net available hydraulic head (m), $\eta_{turbine}$ =
micro-turbine efficiency.

2.3. Optimization and Variable Frequency Drive (VFD) Dynamics
To evaluate the impact of flow regulation via Variable Frequency Drives (VFDs) versus conventional throttling gates, Affinity Laws are applied:

$$P_1 / P_2 = (N_1 / N_2)^3$$

Where: P = power consumption, N = rotational motor speed (RPM). Demonstrates cubic power reduction with
speed adjustments.

2.4. Techno-Economic and Environmental Metrics
The feasibility of integrating renewable energy sources into reservoir management is evaluated using three core indicators:
1) Levelized Cost of Energy (LCOE):

$$LCOE = [\ \Sigma\ (I_t + M_t) / (1 + r)^t\ ] / [\ \Sigma\ E_t / (1 + r)^t\ ]$$

Where: I_t = investment expenditure, M_t = O&M cost, E_t = energy generated, r = discount rate, t =

operational year.
2) Water Savings via Evaporation Reduction (E_{saved}):

Computed using standard Penman-Monteith evaporation equations modified for shaded water



surface area under FPV arrays.

3) Carbon Offset (CO_2 Reduction):

Calculated by multiplying total renewable energy generated by the specific grid emission factor (kg CO_2/kWh).

Conclusion

This study establishes the theoretical and mathematical foundations for optimizing energy efficiency in water reservoir technological operations through the strategic integration of renewable energy sources and advanced drive automation. By analyzing the water-energy nexus across core reservoir functions—including pumping, level regulation, sediment control, and SCADA monitoring—the research highlights significant potential for energy reduction, operational reliability, and environmental sustainabilityThe main theoretical and practical outcomes of this research are summarized as follows:

1. **Hydraulic and System Efficiency Optimization:** Implementing mathematical energy balance models demonstrates that addressing combined motor, mechanical, and hydraulic losses can improve overall pumping system efficiency by 15–20%. Utilizing Variable Frequency Drives (VFDs) governed by Affinity Laws achieves a 20–30% reduction in power consumption compared to traditional mechanical throttling.

2. **Synergistic Renewable Integration:** Integrating Floating Photovoltaic (FPV) arrays provides a dual benefit: the cooling effect of the water body enhances photovoltaic output efficiency by 5–12%, while array shading significantly reduces surface water evaporation. Additionally, micro-hydrokinetic systems installed at spillways and irrigation outlets effectively capture excess hydraulic energy for localized facility power.

3. Economic and Environmental Viability: Techno-economic modeling confirms that hybrid renewable energy deployments (FPV, micro-hydro, and VFDs) offer favorable L

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