Enhancing Efficiency and Sustainability: Green Energy Solutions for Water Supply Companies[1]

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Abstract. *Water supply enterprises significantly impact local communities by providing essential services. These companies face high electricity costs for water extraction, purification, and transportation, affecting efficiency and reliability. Therefore, implementing innovative technologies to enhance sustainability in the water supply sector is crucial. This article explores the opportunities and strategies for renewable energy transition at water supply companies. Using investment, sensitivity, and strategic analyses, as well as a case study approach, the research examines technologies, conceptual frameworks, mechanisms, and approaches to integrate green power into water supply operations, addressing high energy costs and promoting sustainability. The article identifies solar, wind, hydroelectric, biomass, and geothermal energy technologies as the most prominent renewable power solutions for water supply enterprises. The developed conceptual framework for implementing these technologies includes needs assessment and goal setting; resource assessment and technology selection; system design and integration; financing and investment; regulatory compliance and permitting; stakeholder engagement and capacity building; and monitoring, evaluation, and continuous improvement. The mechanisms and approaches to integrate green energy solutions within the developed framework can involve on-site renewable energy generation, power purchase agreements, energy storage and microgrid systems, energy efficiency and demand management, and collaborative and community-based models. As a case study, the article examines a 120-kW solar power plant project for a water supply enterprise,*

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demonstrating profitability with a net present value of 60,370 USD and an internal rate of return exceeding 21%. The project's payback period is estimated at 8.38 years, acceptable within industry standards. Sensitivity analysis indicates the project's financial resilience. Increasing electricity prices will boost profitability, justifying the solar power plant investment amid inflation and economic instability. Additionally, the project ensures reliable water transport and environmental benefits by reducing CO2 emissions through solar energy use. Thus, transitioning to renewable energy at water supply enterprises is feasible and essential for long-term sustainability, transforming operations to be more resilient, efficient, and environmentally friendly.

Keywords: *efficiency, investment analysis, mechanism, renewable energy, strategy, sustainability, transition, water supply enterprise.*

JEL Classification: *O22, O13, P28, Q42*

1 Introduction

The water supply business plays a crucial role in both national and local economies, providing essential needs for the population and businesses. A distinctive feature of this industry is its high dependence on electricity, as activities such as water extraction, pumping, purification, distribution through water supply networks, wastewater disposal, and disinfection require significant amounts of electrical energy to operate the corresponding equipment (Harasymchuk et al., 2024; Hong et al., 2023; Lako et al., 2024; Li et al, 2024; Zakariazadeh et al., 2024). Therefore, the search for and implementation of energy-saving measures in water supply enterprises is the top priority to ensure the economic sustainability of these businesses, as their energy expenses can account for up to 70% of all production costs (Bhojwani et al., 2019; García-Valiñas et al., 2023; Meschede, 2019; Reis et al., 2023; Zubrowska-Sudol et al., 2023).

The integration of renewable energy sources has emerged as a promising strategy to address these challenges while advancing environmental objectives (Bhatraj et al., 2024; García et al., 2022; Glekas, 2008; Iskhakova et al., 2024; Jain & Khare, 2024; Vieira & Ramos, 2008). Today, developing optimal management strategies and considerations involved in harnessing renewable energy within water supply enterprises to reduce operational costs and enhance sustainability is extremely relevant.

Taking into account the relevance of implementing green energy solutions for water supply enterprises, ***the article aims*** to explore the opportunities and strategies for renewable energy transition at a water supply enterprise. Using investment, sensitivity and strategic analyses, as well as the case study approach, the research examines technologies, conceptual framework, mechanisms and approaches to integrate renewable energy into water supply operations, address high energy costs and promote sustainability.

2 Renewable energy technologies applicable to water supply enterprises

The overview of renewable energy sources applicable to water supply enterprises encompasses a diverse array of sustainable options aimed at powering various aspects of water supply operations. These sources offer environmentally friendly alternatives to traditional fossil fuels, contributing to reduced carbon emissions and enhanced sustainability. Key renewable energy sources applicable to water supply enterprises include (Sotnyk & Duan Wenjuan, 2023; Sotnyk et al., 2024):

1) solar energy. Water supply enterprises can harness solar energy through photovoltaic (PV) panels or solar thermal systems. PV panels convert sunlight directly into electricity, while solar thermal systems use sunlight to heat water or other fluids for various applications within water treatment plants, pumping stations, and distribution networks (Shrestha, 2005; Tawalbeh et al., 2021);

2) wind energy. Water supply enterprises situated in regions with consistent wind patterns can benefit from wind energy to supplement their electricity needs. Wind turbines can be installed on-site or in nearby locations to generate clean and sustainable power for water pumping, treatment, and distribution processes (Ramos et al., 2011; Vieira & Ramos, 2008);

3) hydroelectric power. Water supply enterprises located near rivers, streams, or other water bodies with suitable hydraulic conditions can leverage hydroelectric turbines to produce renewable energy. These turbines can be integrated into existing water infrastructure, such as dams or water treatment facilities, to generate power while ensuring efficient water management (Vieira & Ramos, 2008);

4) biomass energy. Water supply enterprises can utilize biomass-derived fuels to generate heat and electricity for various operational needs, including heating water, powering boilers, or generating electricity (Cherchi et al., 2015; Kurbatova et al., 2023);

5) geothermal energy. While less commonly applied in water supply enterprises compared to other renewable sources, geothermal energy can still offer sustainable solutions, especially in regions with accessible geothermal resources. Geothermal heat pumps can be utilized for heating water or spaces within water treatment facilities, contributing to energy efficiency and cost savings (Lee & Younos, 2018; Lourenço et al., 2024; Reis et al., 2024).

The diverse range of renewable energy sources available to water supply enterprises presents opportunities for reducing reliance on conventional energy sources, lowering operational costs, and minimizing environmental impact. By strategically integrating renewable energy technologies into their infrastructure and operations, water supply enterprises can enhance their sustainability and contribute to global efforts towards combating climate change.

3 Conceptual framework for developing renewable energy solutions at water supply companies

Building strategies and estimating their efficiency in the water supply industry requires a solid conceptual framework. The latter provides a structured approach to guide decision-making, planning, and implementation processes, ensuring alignment with organizational goals, technical requirements, and sustainability objectives. The essential components of the conceptual framework are presented in Table 1.

4 Management mechanisms and approaches for integrating renewable energy into water supply operations

The developed conceptual framework allows careful consideration of various models, mechanisms and approaches to ensure optimal utilization of resources, cost-effectiveness, and sustainability. The most popular management mechanisms, models, and approaches commonly used for integrating renewable energy into water supply operations are as follows (Cherchi et al., 2015; Coelho & Andrade-Campos, 2014; Kurbatova et al., 2021, 2024; Lee & Younos, 2018; Melnyk et al., 2023; Sotnyk et al., 2019, 2022a; Szpak et al., 2024; Yu-Xia Tu et al., 2022):

1. On-site renewable energy generation.

This approach involves installing renewable energy generation systems directly at water supply facilities, such as treatment plants, pumping stations, and distribution networks. For this, common technologies include solar PV panels, wind turbines, micro-hydro turbines, and biomass energy systems. On-site generation allows water supply enterprises to produce clean energy locally, reducing reliance on grid electricity and mitigating energy costs and environmental impact.

2. Power Purchase Agreements (PPAs).

PPAs enable water supply enterprises to procure renewable energy from third-party developers or energy service providers without upfront investment in equipment and infrastructure. Under a PPA, the water utility agrees to purchase electricity generated from renewable sources at a predetermined rate over a specified contract period. This model offers financial flexibility, risk mitigation, and access to renewable energy without the burden of ownership, maintenance, or operational responsibilities. It is quite convenient for water supply companies, however, the price of such services and benefits can be high.

3. Energy storage and microgrid systems.

Energy storage technologies, such as batteries and pumped hydropower storage, complement renewable energy generation by storing excess energy for use during periods of high demand or low renewable resource availability. Microgrid systems integrate renewable energy sources, energy storage, and conventional grid connections to create resilient and self-sufficient energy networks. Water supply enterprises can deploy microgrid systems to optimize energy supply, enhance reliability, and minimize disruptions, particularly in remote or off-grid locations. The main drawback of this solution is the high value of energy storage technologies, preventing their wide use at different water supply companies.

4. Energy efficiency and demand management.

Improving energy efficiency and implementing demand management measures are critical components of renewable energy integration in water supply operations. Water utilities can reduce energy consumption through equipment upgrades, process optimization, leakage reduction, and energy-efficient technologies. Demand management strategies, such as peak shaving, load shifting, and demand response programs, help balance energy supply and demand, optimize energy use, and reduce utility costs.

5. Collaborative and community-based models.

Collaborative models involve partnerships between water supply enterprises, local communities, government agencies, non-profit organizations, and private sector stakeholders to develop and implement renewable energy projects. Community-based models prioritize community engagement, ownership, and benefit-sharing, empowering local stakeholders to participate in renewable energy initiatives and gain social,

Table 1 The conceptual framework for developing renewable energy solutions at water supply companies

Element of the framework	Characteristics of the element
1 Needs assessment and goal setting	– a comprehensive assessment of energy needs, consumption patterns, and operational requirements within the water supply system of the settlement and the water supply company; – definition of clear goals and objectives for renewable energy integration, considering factors such as cost reduction targets, environmental sustainability goals, and energy security priorities of the water supply company and local communities.
2 Resource assessment and technology selection	– evaluation of available renewable energy resources, including solar, wind, hydro, and biomass potential, through site assessments and feasibility studies that can be potentially applied to the water supply company and local communities; – selection of appropriate renewable energy technologies based on resource availability, site-specific conditions, technical feasibility, and economic viability to implement on-site.
3 System design and integration	– design of renewable energy systems and infrastructure to meet specific energy demand profiles, operational constraints, and regulatory requirements of the territory and the company; – integration of renewable energy generation components seamlessly with existing water supply infrastructure, such as treatment plants, pumping stations, and distribution networks.
4 Financing and investment	– development of a financing strategy to fund renewable energy projects, considering capital costs, operational expenses, financing options, and return on investment; – exploration of various funding sources and mechanisms, including grants, incentives, loans, public-private partnerships, and innovative financing models.
5 Regulatory compliance and permitting	– compliance with relevant regulatory frameworks, standards, codes, and permitting requirements governing renewable energy development and water supply operations; – obtaining necessary permits, approvals, licenses, and environmental assessments for renewable energy installations, addressing legal, environmental, and social considerations.
6 Stakeholder engagement and capacity building	– engagement of stakeholders, including staff, management, government agencies, local communities, and industry partners, throughout the renewable energy development process; – building internal capacity through training, awareness campaigns, knowledge sharing, and skill development initiatives to support effective renewable energy management and operation.
7 Monitoring, evaluation, and continuous improvement	– establishment of monitoring and evaluation mechanisms to track the performance, efficiency, and impact of renewable energy systems over time; – regularly review and data analysis, identification of opportunities for optimization and improvement, and implementation of corrective actions to enhance system performance and reliability

Source: (García-Valiñas et al., 2023; Lako & Çomo, 2024; Reis et al., 2023; Sotnyk et al., 2021; Zakariazadeh et al., 2024)

economic, and environmental benefits. This scheme is the most promising to implement for depressed or low-income territories where water supply companies belong to or are subsidized by the municipalities.

By leveraging these models, mechanisms and approaches, water supply enterprises can effectively integrate renewable energy into their operations, optimize energy management, reduce carbon emissions, and contribute to sustainable development and resilience in the water sector. Therefore, the next stage of our research is the analysis of a case study on implementing a small solar power plant at a water supply company to ensure the self-production of electricity to satisfy its needs in energy and enhance sustainability.

5 Case study: renewable energy development at a water supply enterprise

Economic substantiation of a green energy project. Let us consider a water supply enterprise that serves a city with 200 thousand inhabitants. Based on technical and economic feasibility, it is proposed to implement a pilot project to construct a

120-kW solar power plant. The estimated monthly electricity generation volumes of the solar power plant for its first year of operation are provided in Figure 1.

Based on the data in Figure 1, in the first year, the solar power plant will generate 174.8 thousand kWh of electricity, while the enterprise's annual consumption is 1112.4 thousand kWh, corresponding to an average electricity substitution rate of 15.6%. In subsequent years, the electricity generation by the solar power plant will decrease by 0.8% annually due to technically objective degradation of the solar panels (annual decrease in the productivity of solar panels). The operational lifespan of the solar power plant is assumed to be 25 years. The monthly electricity consumption volumes are assumed to remain constant for the lifespan of the plant's operation. The calculation of the annual electricity production volumes by the solar power plant for the next 25 years shows that the average share of substituting purchased electricity with self-generated electricity will reduce from 15.6% (174.8 thousand kWth in the first year) to 12.8% (144.2 thousand kWth in the 25th year). It is assumed that the annual volume of green electricity generation, which compensates for part of the enterprise's annual electricity consumption, is taken into account, and monthly electricity flows are not considered since they are reserved for the company by default through the net-metering or net-billing system.

The project's incomes are determined by the savings obtained from reducing the volume of electricity purchased by the water supply enterprise for powering equipment, due to the use of solar energy for these needs. Investment costs for the project include the cost of purchasing equipment, conducting installation and commissioning works, designing, and expenses for dismantling and decommissioning the equipment after the solar power plant's operational life ends. Annual operational costs for maintaining the solar power plant include annual depreciation charges and other expenses for the ongoing maintenance of the solar power plant.

Information on the cost of equipment and installation works is based on the vendors' prices. Decommissioning costs after the solar power plant's operational life were calculated as 5% of the initial investment costs according to the recommendations (European Commission, 2015). Annual depreciation charges over the entire equipment usage period were calculated using the straight-line method. The discount rate was set at 15%, considering the project's risk level and assuming that the project's investment costs are formed in a 50/50 ratio of own and borrowed resources. All calculations were conducted in US dollars (USD). The initial data for the solar power plant installation project are presented in Table 2.

Since the generated electricity will be used for internal needs and not sold externally, this activity is not subject to state taxation.

To assess the economic feasibility of implementing the pilot project, we performed an investment analysis, calculating the following indicators (Melnyk, 2012; Sotnyk, 2021, Sotnyk et al., 2020, 2022, 2023):

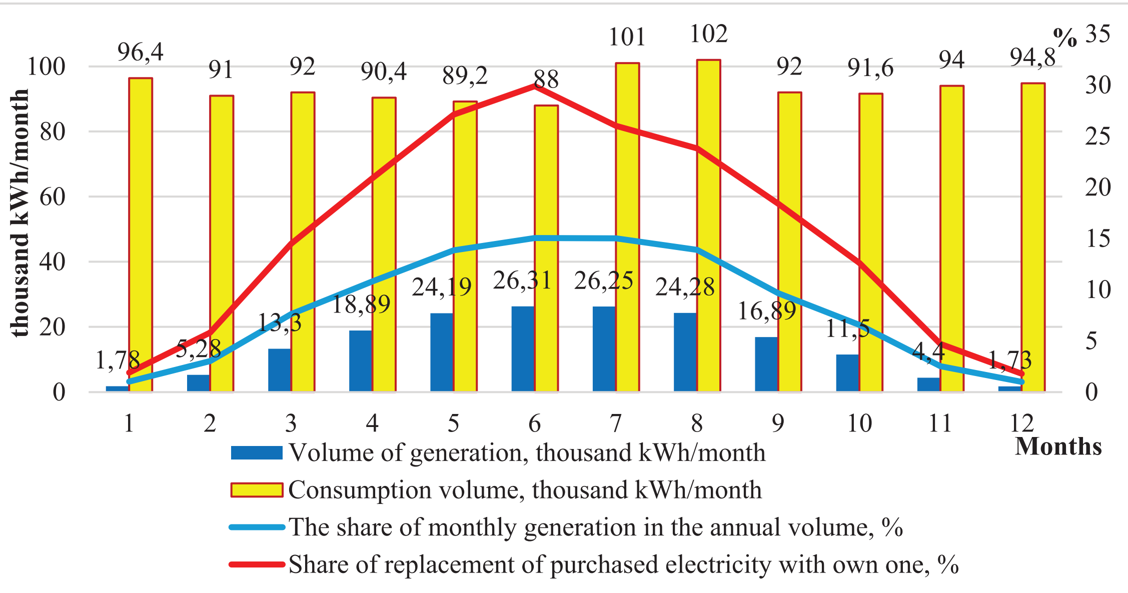

Figure 1 Average forecasted monthly generation, consumption, and substitution of electricity at the solar power plant of the water supply enterprise

Table 2 Initial technical and economic data for the solar power plant installation project at the water supply enterprise (based on vendors' prices)

Indicator	Indicator Value
Investment costs, thousand USD	169.33
– Cost of equipment purchase (hybrid power plant of 30 kW + grid power plant of 90 kW), thousand USD	149.99
– Installation and commissioning costs, thousand USD	8.25
– Design costs, thousand USD	3.03
– Decommissioning cost, thousand USD	8.06
Annual operational costs, thousand USD/year	7.49
– Annual depreciation charges, thousand USD/year	6.77
– Annual maintenance costs, thousand USD/year	0.72
Purchase price of electricity for the enterprise, USD/kWh	0.21

– Net Present Value – *NPV*;
– Internal Rate of Return – *IRR*;
– Discounted Payback Period – *DPP*;
– Profitability Index – *P*.

According to the results, the project is profitable, with an NPV of 60,370 USD. The IRR is 21.35% at a discount rate of 15%. Therefore, the project has a financial safety margin and remains viable even with a slight increase in the discount rate, but not exceeding IRR. The discounted payback period is 8.38 years, which is acceptable for energy investment projects of this scale. The profitability index is 1.37.

Next, we conducted a sensitivity analysis of the investment project to detect the changes in the project's efficiency indicators caused by external factors, which may potentially alter the discount rate and electricity prices. For changes in the economic situation and, accordingly, the discount rate, we considered, all other things being equal, an increase in the discount rate to 18% and a decrease to 10%. For price changes, we assumed an increase in electricity prices by 15%, 30%, 50%, and 100%. In these scenarios, we examined how all project efficiency indicators behaved. The calculation results are presented in Table 3.

According to the conducted sensitivity analysis, an increase in the project's discount rate, which corresponds to the rising cost of money needed for investment in the project, negatively impacts the profitability of the solar power plant, reducing the project's NPV by more than half – from 60,370 USD down to 27,360 USD. Conversely, a decrease in the discount rate to 10%, i.e., by 5 percentage points, increases the project's NPV by more than double – from 60,370 USD up to 145,650 USD. Moreover, an increase in the discount rate significantly lengthens the project's discounted payback period (by 2.5 years), while a decrease in the rate shortens the payback period by almost 2 years. The change in the discount rate does not affect the IRR; however, an increase in the rate reduces the project's PI to 1.17, while a decrease raises the PI to 1.9.

An increase in the purchase price of electricity positively influences all indicators of the project's investment efficiency. The higher price leads to greater cost savings for the water supply enterprise at the same investment and running costs, significantly increasing the project's profitability. For example, a 15% increase in electricity prices shortens the project's payback period by nearly 2 years, increases NPV from 60,370 USD to 94,350 USD, raises PI from 1.37 to 1.58, and boosts the IRR from 21.35% to 24.83%, indicating enhanced financial strength of the project. Further increases in the purchase price continue to enhance the project's profitability. For instance, a 50% price hike increases NPV by 2.87 times, IRR by 1.54 times, shortens the discounted payback period almost by half, and raises PI by 1.5 times. If the price doubles, NPV grows by 4.75 times, IRR by

Table 3 Results of the sensitivity analysis of the investment project for the construction of the solar power plant

Indicator	Indicator value					
	Discount rate		Electricity price increase			
	10%	18%	+15%	+30%	+50%	+100%
NPV, thousand USD	145.65	27.36	94.35	128.33	173.64	286.91
IRR, %	21.35		24.83	28.28	32.86	44.26
DPP, years	6.46	10.71	6.48	5.32	4.31	2.93
PI	1.9	1.17	1.58	1.79	2.08	2.78

2.08 times, the discounted payback period shortens almost by three times, and PI increases by more than 2 times. Thus, in conditions of inflation and economic instability, the project of implementing the solar power plant at the water supply enterprise becomes more profitable, indicating its economic feasibility.

Non-economic benefits of the project. A significant technological advantage of the project is ensuring the reliability of the technological process of transporting drinking water from the well to the consumer. The social impact of the solar power plant construction project is determined in two interrelated directions: positive impact on water supply/sewerage tariffs and more reliable delivery of sanitary-quality water for the population and critical infrastructure facilities (Sotnyk & Duan Wenjuan, 2023).

The environmental impact of the solar power plant project implementation involves reducing CO2 emissions by replacing traditional electricity produced using fossil fuels with green electricity generated from solar radiation. The volumes of renewable electricity generated by the solar power plant over its 25 years of operation, which will be entirely used for the enterprise's needs, will replace the corresponding volumes of electricity that would potentially be produced using natural gas or lignite. The calculations of the environmental effect of the solar power plant construction and operation are presented in Table 4.

Thus, the project for the construction of a solar power plant at the water supply enterprise, in addition to economic benefits, has positive social, technological, and environmental consequences, including improving the quality and reliability of water supply and sewage systems in the city, reducing atmospheric pollution by decreasing the carbon footprint, and more. Its implementation will allow the enterprise to enhance transitioning to the use of green energy from autonomous sources, managing renewable power development in the water supply sector of the territory.

6 Conclusions

Alongside municipal energy companies, a substantial portion of production costs for water supply enterprises is allocated to electricity for water extraction, purification, transportation, and other associated processes. Therefore, optimizing energy consumption for water supply enterprises through the application of innovative renewable energy technologies is a significant contribution to their stable operation and the development of their production capacities. Managing renewable energy development at a water supply enterprise presents both significant challenges and substantial opportunities. Therefore, this paper explored how integrating renewable energy sources can enhance sustainability and operational efficiency of water supply systems.

Key challenges include the intermittency and reliability of renewable energy sources, high initial investment costs, grid integration complexities, land use concerns, and regulatory hurdles. These obstacles necessitate strategic planning and innovative solutions, such as advanced energy storage technologies, smart grid systems, and supportive policy frameworks.

Conversely, the opportunities offered by renewable energy are considerable. Technological advancements are reducing costs and improving efficiency, creating economic growth and job opportunities. Renewable energy can enhance energy independence and security while delivering profound environmental benefits by reducing greenhouse gas emissions. Additionally, the development of decentralized energy systems

Table 4 Evaluation of the environmental effect of the investment project

Indicator	Indicator value
Total generation of green electricity by the solar power plant over 25 years, thousand kWh	3975
Specific CO_2 emissions, kg/MWh during electricity production using (Technical, 2023):	
– natural gas	277
– lignite	433
Reduction in CO_2 emissions on an annual basis when replacing traditional generation with solar power, tons/year, for:	
– natural gas combustion	44
– lignite combustion	69
Reduction in CO_2 emissions over 25 years, when replacing traditional generation with solar power within the project, tons, for:	
– natural gas combustion	1101
– lignite combustion	1721

can empower local communities and improve resilience.

The study examines the prospects of implementing a 120-kW solar power plant project to meet the energy needs of an urban water supply enterprise. The investment analysis conducted on the water supply company's project demonstrates its profitability, with NPV of 60,370 USD and IRR exceeding 21% at a 15% discount rate. The solar power plant project's payback period is estimated at 8.38 years, which is acceptable.

Sensitivity analysis indicates the project's resilience even with a discount rate increase to 18%, maintaining the financial strength of the project with a discounted payback period of up to 10.71 years. Moreover, escalating electricity purchase prices significantly boosts project profitability, rendering the investment in the solar power plant economically justified. Therefore, amid inflation and economic instability, the implementation of the solar power plant project at the water supply company becomes more profitable, indicating the economic viability of investing in it and the strategic importance of the project for the enterprise's further development. In addition, the project offers technological advantages by ensuring reliable water transport processes and environmental benefits by reducing CO_2 emissions through the substitution of traditional energy sources with solar power.

To summarize, enhancing the transition to renewable energy at water supply enterprises is not only feasible but also essential for long-term sustainability. The integration of renewable energy resources can transform water supply operations, making them more resilient, efficient, and environmentally friendly.

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