Optimizing Water and Energy Efficiency in Jordan: Challenges, Opportunities, and Sustainable Solutions for the Future

Mohamad I. Alwidyan[*1], Amal I. Jaradat[2], Omar A. Ahmad[3], Anwar Al Assaf[4]

[1]Mechanical Engineering Department, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan.
[2] Mechanical Engineering Department, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan.
[3]Department of Civil Engineering,College of Engineering, Amman Arab University, 11953 Amman, Jordan.
[4]Department of Renewable Engineering, College of Engineering, Amman Arab University, 11953 Amman, Jordan.

Abstract

This study evaluates energy performance in Jordan's water sector using a water–energy nexus perspective. It identifies operational inefficiencies, characterizes electricity-use patterns, and proposes feasible measures to improve water and energy management. The analysis follows a three-phase design. First, it compiles an energy profile for the northern governorates for 2007–2017. Second, it diagnoses barriers that limit energy-efficiency implementation. Third, it tests targeted energy-saving scenarios. Results show persistent inefficiencies driven by non-revenue water (NRW), aging infrastructure, and limited uptake of energy-efficient technologies. The sector's energy use intensity (EUI) is 3.33 kWh/m3. This value exceeds reference levels reported for Germany (0.63 kWh/m3) and the United States (0.93 kWh/m³). NRW reaches 46% of total production (≈40 million m³). This loss amplifies scarcity and adds an avoidable energy penalty. Electricity consumption increases by 55% during 2007–2017 and peaks in 2016, which raises operating expenditure. The study prioritizes solar photovoltaic integration, pump efficiency upgrades, and improved operating practices to reduce unit energy demand. It also highlights enabling conditions. These include stronger data governance, access to capital, and supportive policy reform. The contribution is a consolidated, sector-specific diagnosis of the energy burden in Jordan's water services, alongside implementable pathways to reduce cost, emissions, and supply vulnerability.

1. Introduction

Jordan is among the world's driest countries and faces severe water scarcity. Per capita water availability remains outlying below the global average. This stress is augmented by population growth, climate change, and geopolitical pressures that raise demand and constrain supply. Al-Qinna et al. (2021) [1] highlight the need for sustainable water management that prioritizes efficiency and innovation. In Jordan, the water–energy nexus is a binding constraint. Pumping, treatment, and distribution require high energy inputs and rely largely on fossil fuels. Haddadin et al. (2020) [2] report high energy necessities across water-supply options, as well as reverse osmosis desalination used to address scarcity. Recent evidence proposes that Jordan's water sector is among the most energy-intensive globally, with Energy Use Intensity (EUI) exceeding international benchmarks [3]. Al-Omari et al. (2023) [4] argue that renewable integration, predominantly solar power, can reduce fossil-fuel dependence and enhance both energy performance and water services. Yet deployment is conditioned by energy-transition restraints, including import dependence, grid restrictions, and political-economy dynamics that shape feasibility and pace [5, 6].

Excess energy use is also driven by ineffective distribution systems and elderly infrastructure, which increase costs, raise operational risk, and weaken service reliability. Loss reduction is therefore crucial to sustainable water and energy management. Decision-support approaches can strengthen implementation by decreasing uncertainty and addressing informational barriers. The Delphi technique is one example, and it has been used to sustenance water conservation planning within Jordan's supply system [7].

Current advances in water–energy management across the Middle East and North Africa (MENA) deliver practical pathways to improve energy efficiency and reduce operational costs. Jordan has strong potential to expand renewable-energy use, mainly solar power, to address water scarcity and energy inefficiencies [8]. Al-Omari et al. (2023) marked that renewables can strengthen water–energy interactions by decreasing fossil-fuel dependence and enhancing the energy performance of water-service operations. Regional experience also designates scalability. Saudi Arabia has progressed in solar-powered purification

* Corresponding author e-mail: widyan@just.edu.jo.

and smart water-management technologies, which are applicable under coupled water and energy constraints. In parallel, artificial intelligence (AI) and Internet of Things (IoT) implementation now support real-time optimization of water distribution. Reported outcomes include energy reductions of up to 20% in selected deployments [9].

Floating solar photovoltaics (FPV) are emerging as an auspicious option in the MENA region. In Jordan, FPV is being evaluated as a dual-purpose intervention that can conserve water while generating renewable electricity. [10-12]announce evidence from Jordan and Egypt indicating that FPV can reduce evaporation and, under specific site conditions, improve photovoltaic performance. In parallel, atmospheric water generation is being industrialized as a complementary supply pathway in contexts where conventional resources are constrained [13].

Atmospheric water harvesting has advanced through engineered systems that generate potable water from ambient air. This approach is particularly appropriate for arid climates such as Jordan's. Aljalil et al. (2007) assessed a 215 W dehumidification unit and reported an optimistic association between relative humidity and water yield. The system produced 137.2 mL/h at 14.0°C and 87.4% relative humidity. Under the identical conditions, it achieved a specific yield of 0.822 L/kWh [14]. The informed cost was comparable to local bottled-water prices, which supports feasibility for niche and decentralized applications. Overall, such technologies enable a dual-use strategy that links renewable energy options with water conservation. This coupling is especially vital in Jordan, where chronic scarcity increases the value of energy-efficient water solutions.

Jordan's policy direction reflects the wider regional shift toward renewable energy. The National Water Strategy 2023–2040 prioritizes solider water governance and expanded adoption of renewable-energy options within water services. It also treats energy productivity in supply systems as a core response to the water–energy nexus [15]. Implementation, however, remains limited by structural barriers. Financing is the dominant constraint. High upfront capital costs, restricted access to proper financing instruments, and weak institutional support continue to delay large-scale deployment. These constraints are strengthened by technical limitations in legacy infrastructure, which increase retrofit intricacy and reduce the pace of efficiency enhancements [16].

Worldwide, demand-responsive pump operation using variable-speed drives (VSDs/VFDs) has frequently been shown to reduce pumping electricity consumption. The major mechanism is improved hydraulic matching between pump output and system demand. This reduces throttling losses and limits chronic over-pressurization. Field studies report significant energy savings under real operating conditions [17]. In addition, optimized control strategies for pump stations equipped with variable-speed pumps can further lower energy use compared with conventional operating practice [18]. Cooperatively, this evidence supports VSD deployment as a reliable utility-scale efficiency measure for Jordan's pumping-dominated supply chain.

Regardless of recent progress, important gaps remain in the evidence base. Experiential research on the economic viability of energy-efficiency measures and renewable-energy integration in large-scale water systems is still limited, particularly for Jordan. More robust assessments are needed for technologies such as solar desalination and smart metering. Pilot initiatives designate technical potential, but policy choices require context-specific economic evidence. This evidence should comprise cost–benefit analyses that reflect Jordan's constraints, including capital scarcity, climatic changeability, and limitations in legacy infrastructure. Long-term sustainability assessments are also required. These studies should quantify environmental effects and life-cycle costs to define suitability for utility-scale deployment.

Available techno-economic work nevertheless suggests feasible pathways. For example, a techno-economic assessment of concentrated solar power (CSP) indicates that CSP integration into water production could reduce energy consumption in Jordan's water systems [19].

The primary objective of this study is to evaluate energy-efficiency performance in Jordan's water sector, with the northern governorates as the focal region due to their high population and associated service pressures. The northern governorates include Irbid, Mafraq, Ajloun, and Jerash. The study categorizes the main sources of inefficiency and develops practical strategies to reduce energy use across water-supply operations. It examines opportunities to integrate renewable energy and advanced technologies, including floating solar photovoltaics, variable-speed drives, and smart water-management systems. It also evaluates implementation barriers, including financing constraints, technical limitations, and policy or regulatory gaps. Finally, the study assesses the feasibility and expected impacts of selected interventions to generate actionable recommendations that support optimized energy use and improved sustainability in Jordan's water systems.

2. Materials and Methods

Water supply system in Jordan is primarily reliant on distant water resources, necessitating energy-intensive operations involving substantial water pumping, boosting, treatment, and distribution infrastructure. This study was systematically organized into three distinct phases, each utilizing varying levels of analysis to provide a comprehensive understanding of energy consumption in the water sector.

2.1. PRISMA-informed evidence identification and selection.

The evidence-synthesis component supporting contextual benchmarks (e.g., international EUI values, NRW–energy linkages, and regional best practices) was reported using a PRISMA-informed workflow[20] Searches were conducted iteratively for the period 2010–2025 in Scopus, Web of Science Core Collection, and Google Scholar, supplemented by publisher platforms (ScienceDirect/Elsevier; SpringerLink) and targeted institutional sources (e.g., MWI, WAJ, YWC; World Bank, OECD, UNDP, IRENA). Because the evidence search was updated during manuscript development and was not initially planned as a standalone systematic review, identification-stage counts are reported as approximate to

transparently summarize screening effort. In total, approximately n = 690 records were identified (databases n = 630; other sources n = 60); after removing duplicates (n = 170), n = 520 records were screened by title/abstract and n = 410 were excluded. Full texts were assessed for eligibility (n = 110) and excluded with reasons (n = 61), including non-utility-scale/non-transferable studies, insufficient methodological transparency (e.g., undefined units or system boundaries), absence of relevant outcomes (EUI/energy/NRW/interventions), duplicate/overlapping datasets, or non-arid/semi-arid utility context. Screening was performed in two stages (title/abstract followed by full-text) by two authors with disagreements resolved by consensus. The final narrative synthesis included n = 49 sources (peer-reviewed n = 39; institutional/technical reports n = 10). PRISMA-style flow diagram illustrated in **Figure 1**.

2.2. Current Profile of Water and Energy in the Northern Governorates

The first phase of the study aimed to establish the current energy profile for the water sector in the northern governorates of Jordan, focusing specifically on the period from 2007 to 2017, with particular emphasis on the year 2016. This phase comprised three sequential steps. The initial step involved the systematic collection of data pertaining to water production rates, the total volume of billed water, and the energy consumption associated with water supply systems, wastewater facilities, and administrative services. The second step entailed a rigorous analysis of this data, through which key energy performance indicators were derived, spanning the social, economic, energy use, and environmental dimensions. These indicators included per capita energy use for water production, per capita water consumption, energy use intensity (EUI) for both water and wastewater sectors, as well as the carbon footprint associated with water production. The final step involved benchmarking these values against international references, providing a comparative evaluation of the water supply EUI and per capita water supply on a global scale.
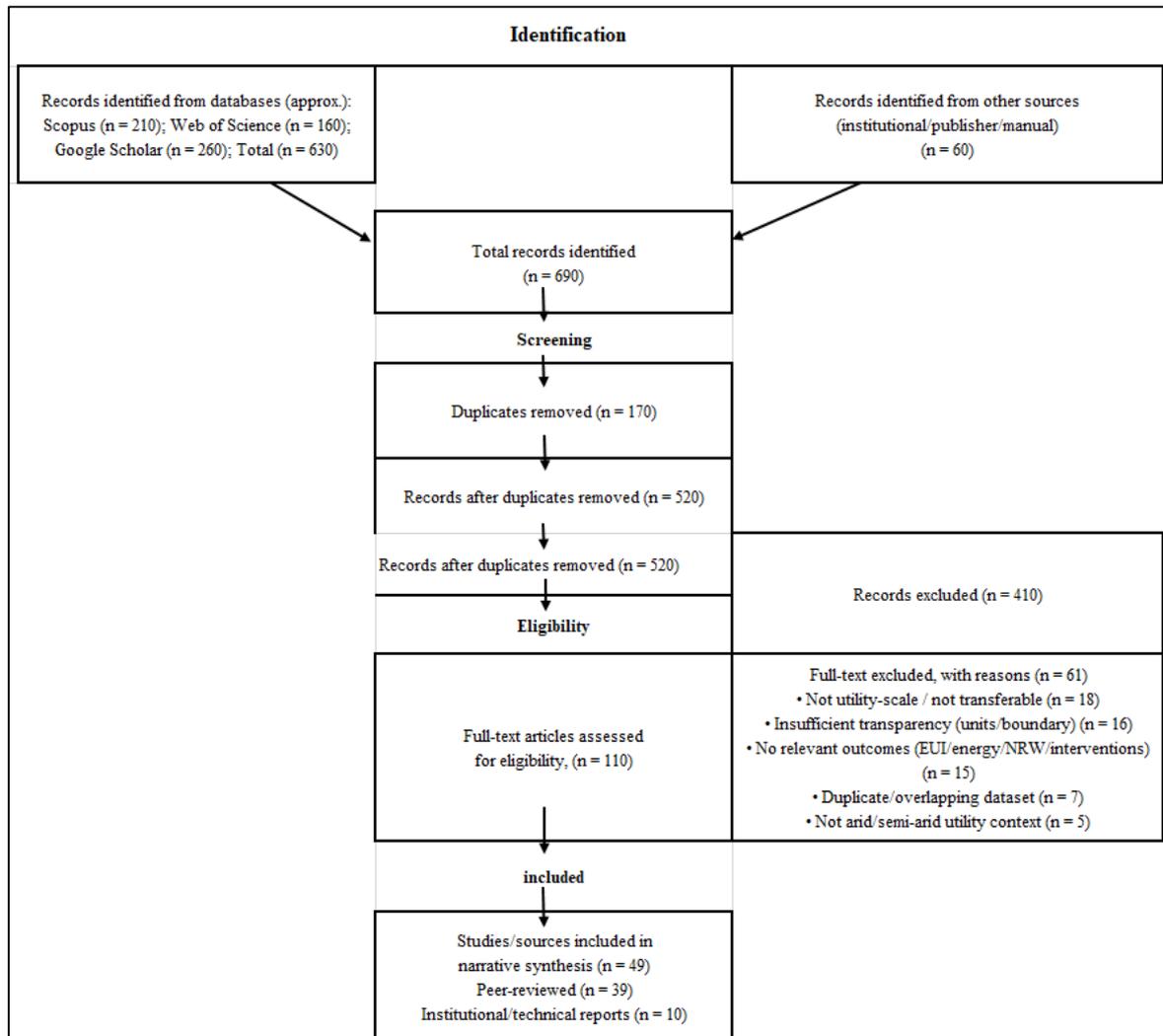

Figure 1. PRISMA-style flow diagram (PRISMA-informed; identification counts approximate). (Source: own study)

Note: Identification-stage counts are approximate because searches were iterative and consolidated export logs were not retained; inclusion counts reflect the final screened and included evidence base (n = 49).

2.3. Barriers to Implementing Energy Efficiency Measures

The second phase focused on identifying and understanding the barriers to implementing energy conservation and efficiency measures, including the adoption of renewable energy systems, within the water sector of Jordan. To achieve this, a structured questionnaire was developed and distributed among employees of the Yarmouk Water Company (YWC) that operate in the northern governorates at all administrative levels, ensuring participation across gender lines. A total of 150 employees were invited to participate, with 138 respondents, yielding a high response rate of 92%. The questionnaire explored a range of potential barriers, categorized into market, informational, financial, technical, and political barriers. Factor analysis was employed to identify the most significant barriers impeding energy-saving initiatives within the sector, which were subsequently addressed through recommendations to overcome these obstacles.

2.4. Energy Efficiency Improvement Scenarios

The final phase was dedicated to proposing and evaluating potential scenarios for reducing energy consumption within the water sector. Three specific improvement strategies considered were: (1) reducing non-revenue water (NRW), (2) implementing energy-efficient technologies, specifically variable speed drives (VSDs) for water pumping systems, and (3) integrating renewable energy sources, particularly photovoltaic solar panels, into the sector's energy supply. For each scenario, the study assumed a 15% reduction in electricity consumption—an ambitious yet achievable target aligned with the Ministry of Water and Irrigation's Energy Efficiency and Renewable Energy Strategy for 2016-2025. Economic and environmental assessments were conducted for each of these scenarios, with calculations based on pilot projects that have already been implemented in the Jordanian water sector.

Energy savings in this study were calculated using the Energy Use Intensity (EUI) metric, which measures the amount of energy consumed per unit of water produced. This metric is a key indicator of the energy efficiency of the water sector and is essential for quantifying improvements made through various energy-saving interventions. The Energy Use Intensity (EUI) is calculated using the following formula:

$$EUI = E / V \qquad (1)$$

where:
E is Energy Consumption (kWh)
V is Water Production (m^3)

To estimate energy savings resulting from proposed interventions (such as the adoption of energy-efficient technologies, renewable energy integration, and non-revenue water (NRW) reduction), the difference between the current energy consumption and the projected energy consumption after the interventions was calculated using the following formula:

$$E_s = E_c - E_p \qquad (2)$$

where:
E_s is Energy Savings (kWh)
E_c is Current Energy Consumption (kWh)
E_p is Projected Energy Consumption after Intervention (kWh)

The reduction in energy consumption due to each intervention was quantified using peer-reviewed, utility-scale evidence. For pumping optimization using variable-speed drives (VSDs/VFDs), efficiency gains were parameterized using published case evidence showing material electricity reductions from demand-responsive speed control and pump-station control optimization [17,18]. For renewable-energy integration (solar PV), offsets to grid electricity demand were based on reported performance of PV-assisted water-sector applications and established PV water-pumping synthesis evidence [12, 22]. For NRW reduction, the assumed energy savings reflect documented relationships between reduced losses, reduced pumped/treated volumes, and lower utility energy consumption in Jordan and comparable utility contexts [23, 24]. The energy savings from NRW reduction were calculated using the following formula:

$$ESR_{NRW} = VR_{NRW} \; x \; EU_W \qquad (3)$$

where:
ESR_{NRW} is Energy savings from NRW reduction (kWh)
VR_{NRW} is Volume of NRW reduced (m^3)
EU_w is Energy use per unit of water (kWh/m^3)

Each of these interventions was modelled separately, and the total energy savings from all interventions were aggregated to calculate the overall impact on the water sector's energy consumption.

By comparing energy consumption before and after the implementation of energy-saving technologies and measures, the study provides a clear picture of ~~the~~ potential energy savings, which are crucial for reducing operational costs and enhancing sustainability in the water sector.

3. Results and Discussion

The data presented from the period 2007 to 2017 illustrates a robust growth in water production rates for YWC. Total water production increased by 25% over the decade, rising from 68 million m³ in 2007 to 89 million m³ in 2017. This increase is indicative of the rising water demand, which is driven by population growth, urbanization, and perhaps agricultural needs within the northern governorates of Jordan. The graphical representation of water production growth rates (see Figure 2) clearly reflects this upward trajectory, with consistent annual increases until 2017.

A detailed inspection of the data shows an even steeper rise in water production between 2014 and 2017, where the rate surpassed the 20% growth mark, reflecting a higher demand likely due to increased temperatures during summer months, urban expansion, and evolving industrial needs. In fact, Figure 2 suggests that water production does not merely increase but accelerate, emphasizing the urgent need for strategic water resource management to keep pace with the growth in demand. The rising trend aligns with national concerns regarding water scarcity, underscoring the importance of sustainable resource management practices.

Furthermore, the growth rate of water production indicates a synergy between increased resource extraction (primarily from groundwater wells) and more intensive operational strategies. However, this rapid increase poses a significant challenge in terms of the sustainability of water resources in the long term. Over-extraction from aquifers can lead to progressive groundwater depletion and deterioration in water security in arid environments [25]. In Jordan, this risk is emphasized in national planning documents and recent groundwater sustainability analyses, which highlight the need to balance abstraction with long-term aquifer protection and demand management [15, 26].

The quarterly variation in water production (Figure 3) reflects seasonal demand patterns commonly observed in semi-arid settings, where higher temperatures in spring and summer increase outdoor and irrigation-related water use and elevate household demand [1, 27]. The lower production in winter and fall is consistent with reduced irrigation and cooling needs. These seasonal swings are operationally important because they concentrate stress on pumping, distribution, and scheduling, strengthening the case for targeted efficiency measures and demand management during peak periods [15].
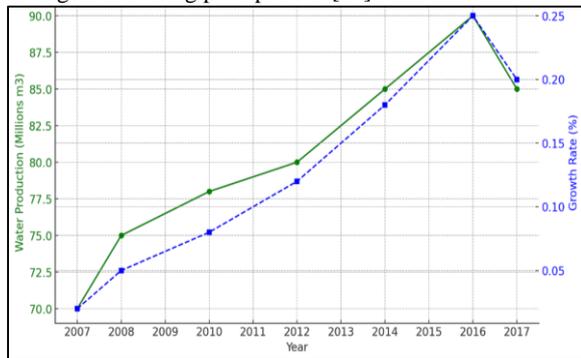

Figure 2. Growth rate of YWC water production from 2007 to 2017 [50]. (Source: calculated from own study)

In addition, the dominance of Irbid as the largest water producer further suggests an uneven distribution of water resources across the northern governorates. The proximity to major groundwater sources in Irbid, along with its significant agricultural base, likely contribute to its high-water production. In contrast, water production in Ajloun and Jerash appears more stable and less dependent on seasonal variability, possibly reflecting lower agricultural and industrial water use. Understanding such regional disparities is crucial for equitable water distribution and ensuring sustainability across the entire network.

The long-term trend of rising water production requires urgent attention from policymakers. Given that groundwater is the primary source, there is a looming risk of depletion, which could lead to severe ecological consequences such as land subsidence, aquifer contamination, and reduced water quality. A transition towards more sustainable water production methods, including development of alternative water resources like desalination or rainwater harvesting, must be seriously considered [26].

Considering the significant growth in water production, YWC and the associated governance structures must also invest in more efficient water management practices, including better infrastructure, leak detection, and recycling. Additionally, public awareness campaigns about water conservation, particularly in high-demand seasons, can play an important role in mitigating pressure on water resources.

The data presented herein highlights the critical need for balancing growth with sustainability. Further studies could explore the environmental and social costs of this continued increase in water production, providing a comprehensive roadmap for mitigating future risks.

YWC (Yarmouk Water Company) serves a significant portion of Jordan's northern governorates, providing water to 317,600 subscribers and wastewater services to 130,937 subscribers. The water production for the year in question was 47,256,249 m³ across the four governorates: Irbid, Mafraq, Jerash, and Ajloun. However, as evidenced by the

data, there is a notable discrepancy between the amount of water produced and the volume of water sold, highlighting substantial inefficiencies in distribution and consumption.
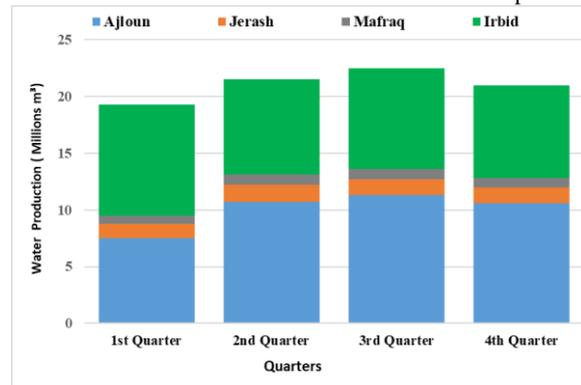

Figure 3. Quarterly Average Water Production by Governorate in 2016 [50].

Figure 4 presents the percentage of water sold per governorate. The data reveals that Irbid is the dominant producer and seller of water, constituting 65% of the total water sold, while Mafraq, Jerash, and Ajloun contribute considerably less to the overall distribution.

These percentages are critical to understanding both the geographic distribution of water resources and the varying levels of water demand in these regions. Irbid's larger population and industrial base contribute to its higher percentage of water sold. This Figure underscores the regional imbalances in water distribution and the need for targeted management strategies to ensure equitable access to water resources.
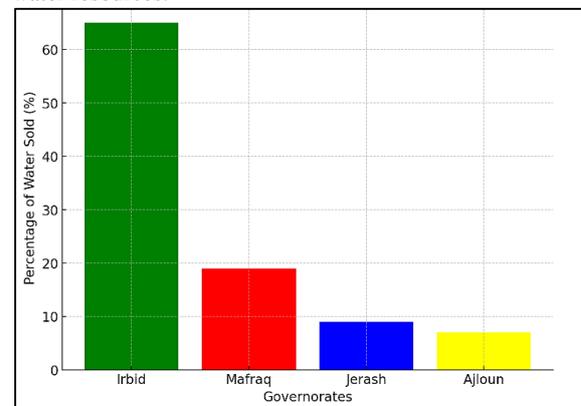

Figure 4. Percentage Distribution of Water Sold per Governorate in 2016 [50].

Non-Revenue Water (NRW) presents a critical challenge to the water sector, not just in terms of water loss, but also in energy wastage. NRW refers to water that is produced but does not generate revenue due to leakage, unauthorized use, and metering errors. In the year of observation, NRW amounted to 40 million m³, or a staggering 46% of total water production.

The high percentage of Non-Revenue Water (NRW) observed can be attributed to several factors. Firstly, metering inaccuracies play a significant role, as outdated or malfunctioning meters fail to accurately register the volume of water consumed, leading to discrepancies in billing and subsequent water loss. Secondly, unauthorized consumption, including illegal connections, contributes substantially to NRW, as water is used without proper metering or payment. Finally, network leakages,

particularly in aging infrastructure, result in significant physical water losses, further exacerbating the issue of NRW. These combined factors highlight the need for improved infrastructure, better metering systems, and stricter enforcement to mitigate water wastage and improve revenue generation.

The high NRW percentage of 46% is alarming, as it not only leads to significant financial losses for YWC but also places immense pressure on water resources. Given the increasing demand for water, reducing NRW should be a priority. Strategies to address this issue include investing in modern metering technologies, implementing stricter monitoring systems, and upgrading the water distribution infrastructure to minimize leakages [28].

The substantial gap between water produced and sold—coupled with high levels of NRW—raises questions about the operational efficiency of YWC and the broader water sector in the northern governorates. Addressing these inefficiencies is critical not only for economic sustainability but also for ensuring equitable access to water resources. Further investment in technology, leak detection systems, and public awareness campaigns on water conservation could mitigate these issues. In line with global water conservation efforts, Jordan could benefit from integrating similar water-saving indicators and strategies, such as the Delphi method, for optimizing water use in municipal systems [7].

Moreover, a detailed understanding of the regional discrepancies in water sales, as shown in **Figure 4**, is essential for more targeted and effective management. Policymakers must address the imbalances between governorates to ensure that water resources are efficiently allocated and that all regions receive fair access.

The energy-consuming components in YWC's water and wastewater systems play a pivotal role in ensuring efficient water supply, wastewater treatment, and the overall functioning of the infrastructure. As noted in **Table 1**, YWC operates several critical energy-intensive facilities across its water supply, wastewater, and support systems. These include water extraction and delivery points, water treatment and wastewater treatment plants, as well as supporting infrastructure for the operation and maintenance of these systems.

The energy-consuming components of the water management process are integral to each stage of the system's operation. In the Water Supply System, energy is required for the extraction, conveyance, and delivery of clean water to consumers. This system includes 317 wells for groundwater extraction, which are major energy consumers due to the need for pumps to lift water from underground sources. Additionally, 162 reservoirs are used for water storage and distribution; although less energy-intensive than wells, they still require energy for pumping and distribution. Furthermore, 92 pumping stations are critical for transporting water across the network, particularly to areas with elevation changes. In the Wastewater System, energy is needed for the treatment of wastewater to ensure safe discharge or reuse. This includes 17 water treatment plants, which consume substantial energy for processes such as filtration and chemical treatments, and 7 sewage lifting stations, which elevate wastewater to ensure it reaches treatment facilities. Moreover, 9 wastewater treatment plants are essential for

removing harmful pollutants, requiring significant energy. Finally, the Support System encompasses the administrative and operational components necessary for the smooth functioning of the entire water management system, including 32 offices for management and monitoring, 8 laboratories for quality control to ensure safe water standards, and 17 maintenance units responsible for the upkeep of infrastructure and equipment to maintain operational continuity.

Table l. Number of energy-using facilities in YWC.

Facility Name	Item's	Total No.
Water Supply System	Well	317
	Reservoir	162
	Pumping Station	92
Wastewater System	Water Treatment Plant	17
	Sewage Lifting Station	7
	Wastewater Treatment Plant	9
Support System	Office	32
	Laboratory	8
	Maintenance Unit	17

The total number of energy-consuming components (see **Figure 5**) across the water supply and wastewater systems is substantial. These systems require continuous energy inputs, which directly contribute to the operational costs of YWC. The reliance on energy-intensive facilities like wells, reservoirs, pumping stations, and treatment plants raises important questions about the sustainability of energy consumption in water management.

The water supply system, being the largest energy consumer, accounts for the most significant portion of energy use, largely due to the high number of wells and pumping/boosting stations. In northern Jordan, groundwater-based supply requires substantial electrical power to lift water and overcome conveyance and distribution head, which is consistent with national assessments that identify pumping as a dominant driver of operating costs in the water sector (Ministry of Water and Irrigation [1, 15]. While arid-region groundwater systems generally face higher energy burdens due to deeper abstraction and long conveyance distances, the Jordanian context is especially sensitive because water resources are spatially distant from demand centers [15, 27].

The wastewater system also represents a major source of energy consumption, reflecting the continuous operation of collection, pumping, and treatment processes. Consequently, efficiency measures and supply-side decarbonization—such as high-efficiency pumping and controls, on-site solar PV for pumping/treatment loads, and improved system-wide energy management—are widely recommended for reducing electricity demand and associated emissions in Jordan's water and wastewater services ([4, 16, 29, 30].

The high energy demand from these facilities necessitates strategies aimed at improving energy efficiency and reducing operational costs. One potential solution is integrating renewable energy sources such as solar power to supplement or replace traditional energy sources for running pumping stations and treatment plants. Additionally, incorporating smart grid systems that optimize energy use and monitor energy consumption in real-time could further reduce waste. The integration of renewable energy technologies like solar power has been a game-changer for desalination in the MENA region. Recent advancements,

such as those discussed by [31], highlight the progress in renewable energy-powered desalination systems, which are becoming increasingly vital for water-scarce regions like Jordan.

Efforts to implement energy-efficient technologies in the water sector will not only lead to reduced operational costs but will also contribute to sustainability goals, particularly in regions that suffer from energy scarcity. Upgrading equipment and ensuring that each component of the system operates at peak efficiency will be paramount in achieving these objectives.

3.1. Electricity Consumption in Water Sector

Trends in electricity consumption within the water sector from 2007 to 2017 reveal significant increases in both consumption and associated costs. **Figure 6** illustrates the consumption of electricity in gigawatt-hours (GWh) and its costs in millions of Jordanian Dinars (JOD) during this period (JOD 1.0 = $1.4). The data shows a consistent upward trend in both electricity consumption and prices, with a marked increase in costs beginning around 2010. Notably, electricity prices saw a substantial rise starting in 2009. In **Figure 6**, the bars represent the electricity consumption (in GWh), while the line graph shows the changes in electricity prices over the same period.

Additionally, **Figure 7** depicts the growth rate of electricity consumption in the water sector, highlighting a significant peak in 2016, with a 55% increase compared to the 2007 levels. This surge in consumption is closely linked to the rising demand for water, driven by factors such as population growth and the influx of refugees, particularly after 2011. These Figures underscore the growing pressure on the water sector's electricity usage, driven by both increasing demand and rising energy costs.
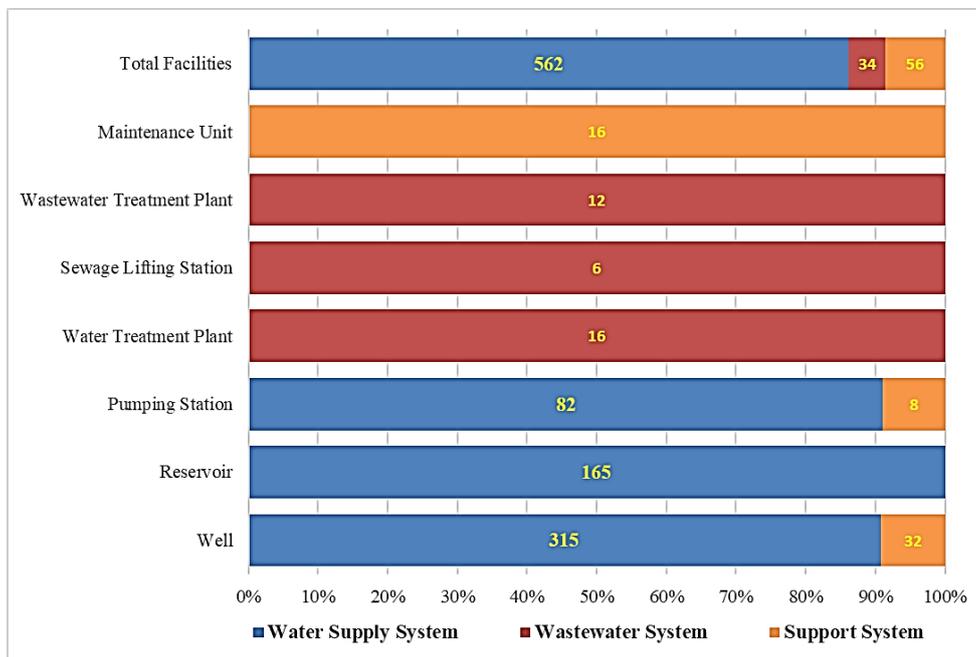

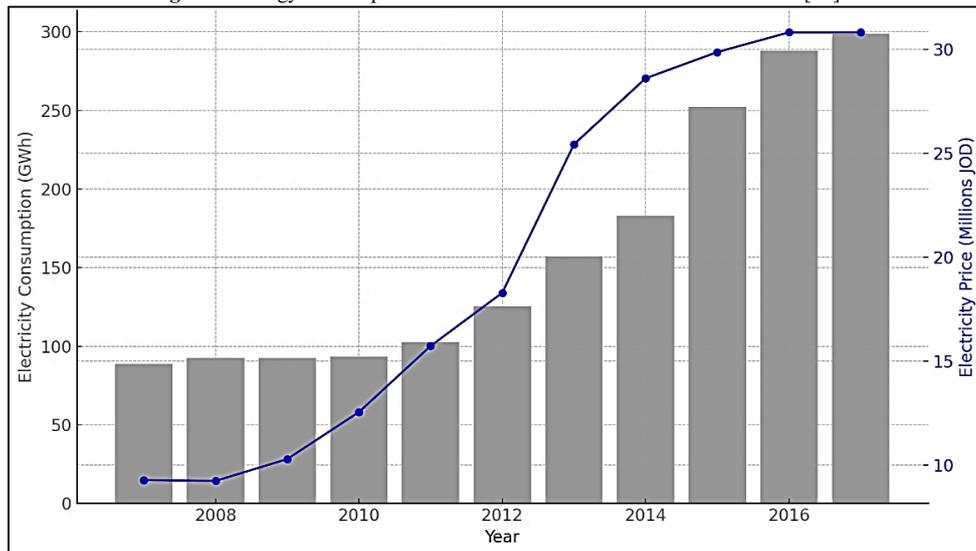**Figure 5**. Energy consumption across YWC water and wastewater facilities [51].

Figure 6. Trends in electricity consumption and pricing in the water sector (2007–2017) [51].

Figure 7 depicts the annual growth rate of electricity consumption. Each point corresponds to the growth rate from the previous year, giving insight into the fluctuation of demand over time.

From 2007 to 2017, the electricity consumption shows rapid growth. The sharpest increases happen between 2013 and 2017, where the consumption increases by more than 100 GWh.

The consistent growth rate shows a clear demand increase in electricity usage, possibly indicating population growth, industrial development, or technological advancements.

The rising electricity consumption in the water sector could be attributed to increased water production and demand, as well as the higher cost of electricity, which has a cumulative growth rate of 147% since 2005. These factors can be explained by the substantial population growth after 2011, which placed additional pressure on water and energy systems.

3.2. Energy Performance Indicators: Social Dimension (Water Supply vs. Consumption)

The per capita water supply in the studied region is reported at 82.59 litters per capita per day (l/c/d), as shown in **Figure 8**, which is significantly higher than the per capita water consumption of 44.91 l/c/d. This discrepancy indicates a substantial gap between the water supplied and the water consumed, suggesting inefficiencies in the water distribution system. The excess water supplied but not consumed may be attributed to losses or wastage in the distribution network before it reaches the consumer. This gap raises important concerns about the efficiency of water infrastructure, including issues such as leaks and the mismanagement of resources. Current trends and research indicate that infrastructure inefficiencies, such as water pipe leaks and poorly maintained distribution systems, are often linked to this high discrepancy between supply and consumption [32]. Addressing these inefficiencies is crucial for optimizing water usage and ensuring sustainable management of water resources.
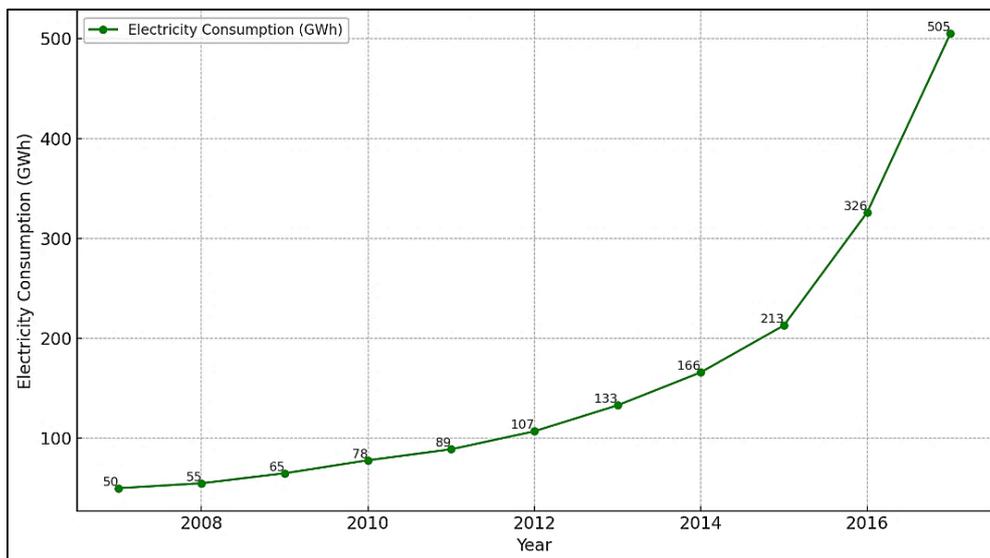

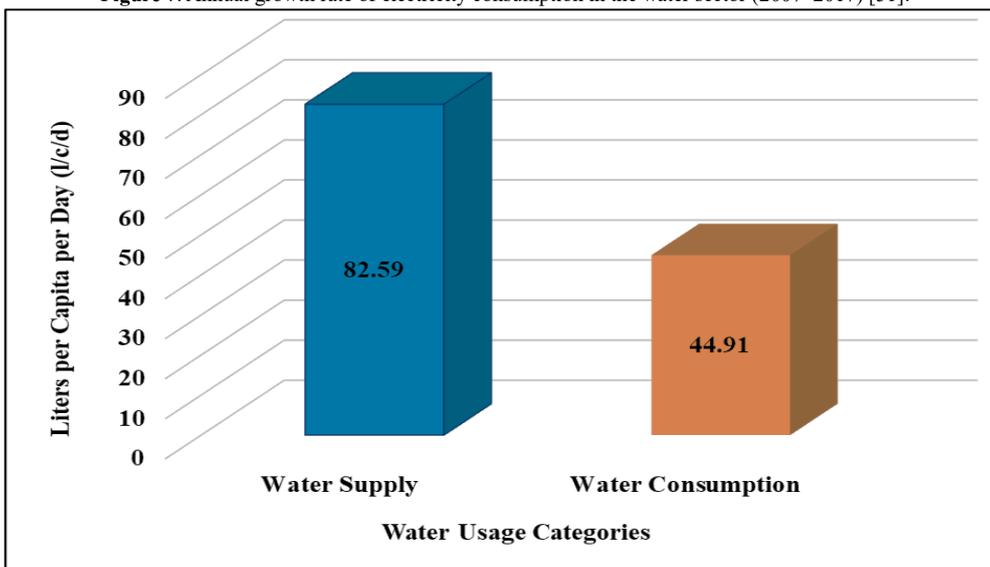**Figure 7**. Annual growth rate of electricity consumption in the water sector (2007–2017) [51].

Figure 8. Social dimension of energy performance indicators: water supply vs. consumption. [50; 51]

3.3. Energy Use Dimension

The Energy Use Intensity (EUI) for the water cycle is 3.61 kWh/m³, as shown in Figure 9, with the water supply EUI slightly lower at 3.33 kWh/m³. The wastewater EUI is notably lower at 0.24 kWh/m³, reflecting the varying energy demands associated with different stages of water treatment processes. These values highlight the significant energy requirements for water supply and wastewater treatment systems, with water supply operations being the most energy intensive. The per capita annual energy use for water production is recorded at 108.79 kWh per capita per year, which represents a substantial amount of energy required to ensure the adequate supply and treatment of water

In the context of global trends, energy consumption in water systems has been increasing due to rising urban populations and the pressures of climate change, which demand more energy-intensive solutions for water purification and supply [33]. This trend underscores the importance of optimizing energy use in water management systems, as doing so can help reduce operational costs and mitigate the environmental impacts associated with high energy consumption.

3.4. Economic Dimension (Water Production Cost)

The energy cost for water production is a critical component of the overall economic burden associated with water supply. As depicted in Figure 10, the per capita energy cost for water production is recorded at 10.36 JOD per capita per year (JOD/c/a), while the energy cost per cubic meter of water produced is considerably lower at 0.34 JOD/m³. This significant difference indicates a high individual cost associated with water production, which can be attributed to inefficiencies within the system or an over-reliance on energy-intensive processes for water treatment.

Recent trends suggest that water production energy costs have been rising globally, as many urban areas increasingly depend on energy-intensive desalination processes or advanced water purification systems. Economists have highlighted that investing in energy-efficient technologies, such as renewable energy-powered desalination, could play a pivotal role in reducing these escalating costs in the future [34]. This underscores the need for technological advancements and the adoption of sustainable practices to improve cost efficiency and reduce the environmental impact of water production.
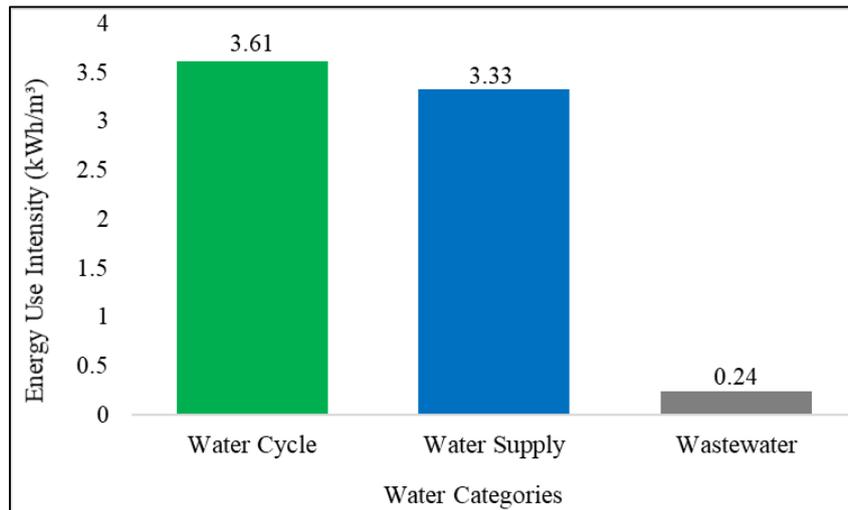

Figure 9. Energy use dimension of performance indicators for water supply and wastewater [50; 51].(Source: calculated from own study)
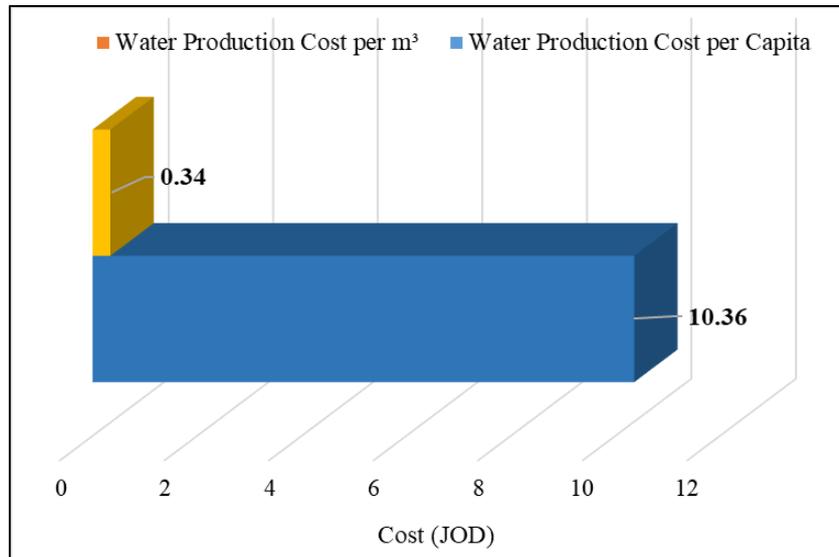

Figure 10. Economic Implications of Energy Consumption in Water Production: Cost per Capita and per m³ [50; 51].

3.5. Environmental Dimension (Carbon Footprint)

The carbon footprint of water supply operations is a significant environmental consideration. As reported, the environmental cost of supplying one cubic meter of water is 2.43 kg CO_2/m^3. This value reflects the carbon emissions associated with water production, particularly when the energy used is derived from non-renewable sources, contributing to the overall greenhouse gas emissions.

Given the rising concern over climate change, there is a growing emphasis on reducing the carbon footprint of water systems by transitioning to cleaner energy sources. For instance, solar-powered desalination has gained attention as a promising solution. Numerous studies have shown that integrating renewable energy into water treatment processes significantly reduces greenhouse gas emissions, positioning it as a key strategy for achieving sustainable water management [21].

The data highlights the substantial energy and environmental footprint of the current water supply system, underscoring the need for strategic improvements. Addressing these challenges requires significant investments in energy-efficient technologies, better infrastructure maintenance, and the widespread adoption of renewable energy sources. Research consistently emphasizes the importance of integrated water-energy management, which optimizes both energy consumption and water usage efficiency, ultimately fostering a more sustainable and low-carbon water sector.

3.6. International Benchmarking:

International benchmarking is used to contextualize the Northern Governorates' water-utility performance using two indicators: (i) service level (per-capita water delivered/available and the implied supply–consumption gap) and (ii) energy-use intensity (EUI) for water supply. Because benchmarking can be distorted by inconsistent system boundaries, comparisons are interpreted with explicit definitions (e.g., utility water supplied/available vs. household end-use, and kWh per m^3 supplied/produced vs. kWh per m^3 billed), consistent with benchmarking practice and the water–energy nexus framing used in Jordan and comparable regions [35-37].

Per-capita water and minimum-service context. Global WASH and human-rights reporting commonly frames basic domestic water needs within an indicative ~50–100 L/person/day range; this is used here strictly as a contextual reference, not as a compliance statement. In Jordan's Northern Governorates, the manuscript reports ~83 L/c/d supplied versus ~45 L/c/d actually consumed, indicating a substantial supply–consumption gap consistent with intermittent delivery and/or network losses. For international context, Germany reports ~120–123 L/person/day average drinking-water consumption (German Federal Ministry (BMUV)). In the United States, typical household water use is on the order of ~82 gallons/person/day (~310 L/person/day; this household-use statistic is reported to avoid conflating domestic use with economy-wide withdrawals.

3.7. Energy-Use Intensity (EUI) in Water Supply

Reported EUI values vary substantially by source water, conveyance head/topography, treatment requirements, and network pressure; therefore, benchmarking should be interpreted as indicative rather than absolute. This interpretation is consistent with regional benchmarking practice and water–energy nexus analyses, which emphasize that cross-country comparisons must account for system boundaries and supply-chain conditions [33, 35].

Accordingly, the international EUI values presented in Figure 12 are treated as contextual reference points, while the Northern Governorates' EUI of 3.33 kWh/m^3 reflects a comparatively energy-intensive supply chain in a water-scarce setting.

Benchmarking supports prioritization of measures that reduce both losses and unit energy demand. First, NRW reduction is directly linked to avoidable energy consumption; NRW-related energy penalties have been quantified and discussed for Jordanian utilities [23, 38].

Second, pump and operational efficiency measures (including optimized pumping and control upgrades) are central to reducing EUI and are consistent with the water–energy nexus priorities identified in Jordan-focused assessments [36, 38].

Third, renewable electricity substitution (e.g., solar PV) can offset pumping/treatment electricity demand where feasible, aligning with Jordan's national strategy direction and policy briefs focused on PV for water pumping/treatment [15, 30], and with regional case-study evidence on FPV where relevant [12].

3.8. Global Trends and Implications

The comparison underscores significant disparities in both water availability and energy efficiency across countries. Developed nations like Germany and the United States demonstrate higher per capita water supply and lower EUI, suggesting more robust infrastructure and efficient resource utilization. In contrast, countries like Jordan face challenges related to water scarcity and high energy consumption in water supply, necessitating targeted interventions.

Addressing these challenges requires a multifaceted approach, including investment in infrastructure, adoption of energy-efficient technologies, and implementation of policies promoting sustainable water and energy use. International collaboration and knowledge exchange can play pivotal roles in bridging these gaps and fostering global water and energy security.

Figure 11 presents a comparison of per capita water supply across several countries, highlighting significant disparities in water access. The United States exhibits the highest per capita water supply, approaching 1,600 litters per capita per day, reflecting its abundant water resources and advanced infrastructure. Germany, while considerably lower, still maintains a relatively high-water supply, indicative of its efficient water management systems. China and Egypt show intermediate levels of supply, with Egypt's lower values reflecting the nation's ongoing water scarcity challenges. Saudi Arabia, characterized by severe water scarcity, displays a significantly reduced water supply, consistent with its reliance on desalination technologies.

Jordan, particularly in its northern provinces, experiences a notably low per capita supply, approximately 80 litters per capita per day, underscoring the country's acute water shortage issues. The northern provinces of Jordan, in particular, face even more critical water constraints. This comparison underscores the global disparity in water access and emphasizes the need for effective water management strategies, especially in water-scarce regions. Countries like Jordan and Saudi Arabia must depend on technological innovations, such as desalination and renewable energy integration, to meet water demand, whereas nations with abundant resources, like the USA and Germany, focus more on sustainability and infrastructure efficiency. These stark differences highlight the challenges faced by developing nations in securing adequate water supplies due to geographical, climatic, and infrastructural limitations.

International studies suggest varying levels of energy efficiency in water systems globally. For instance, countries like Germany have significantly reduced their energy consumption for water supply through advanced water management technologies and renewable energy integration. In the case of Jordan, Al-Omari et al. (2023) argue that renewable energy integration could play a pivotal role in optimizing the water-energy nexus, which remains highly dependent on traditional energy sources.

Figure 12 presents international comparison of energy-use intensity (EUI) for water supply (kWh/m^3). Values are literature-based indicative benchmarks and are context-dependent (source water, treatment level, and distribution head); Germany and U.S. ranges are based on published benchmarking/sector summaries [39, 40], while Jordan reflects the study's computed provincial EUI.

The United States and Germany show relatively low EUI values, with Germany's water supply system operating at 0.63 kWh/m^3 and the U.S. at 0.93 kWh/m^3. These values indicate that both countries have highly efficient water supply systems. Germany's lower EUI reflects its advanced infrastructure, robust water management practices, and the integration of energy-efficient technologies. The U.S., with its well-developed water supply networks, similarly demonstrates effective energy use, though it faces regional variability in EUI due to the diverse geographical and climatic conditions across the country.

In contrast, Jordan exhibits a much higher EUI of 3.33 kWh/m^3, suggesting that the country's water supply system is energy intensive. This elevated EUI can be attributed to several factors, including the reliance on energy-intensive processes such as groundwater pumping, desalination, and water treatment, which are prevalent due to the country's significant water scarcity challenges. Jordan's high energy consumption for water production is compounded by the aging infrastructure, inefficiencies in distribution, and the lack of widespread adoption of energy-efficient technologies like variable speed drives (VSDs) or renewable energy integration.
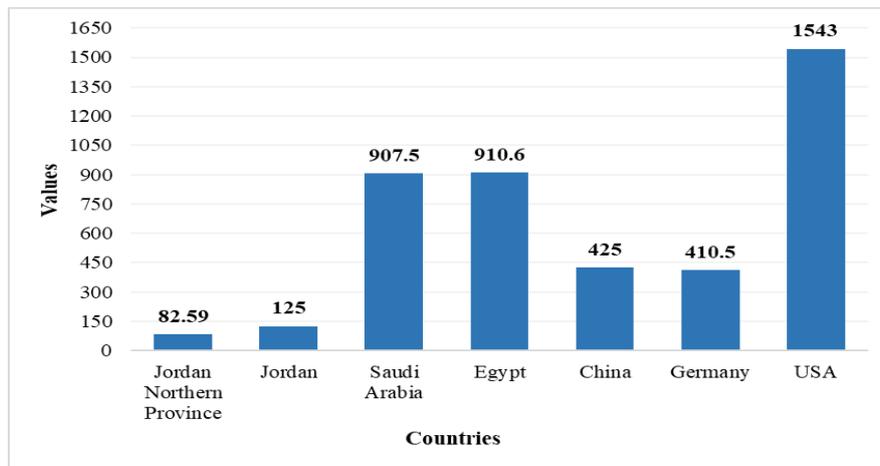

Figure 11: International comparison of per capita water supply (l/c/d) [47; 48].
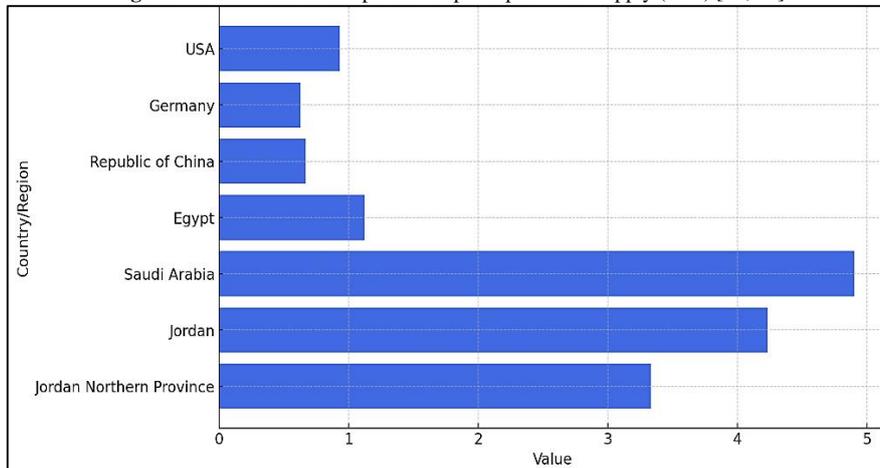

Figure 12: International Comparison of Energy-Use Intensity for Water Supply (kWh/m^3) [33, 35, 37–40, 48].

The high EUI in Jordan highlights the energy-water nexus, where the demand for water is directly tied to energy consumption. As a water-scarce country, Jordan depends on energy-intensive methods such as groundwater extraction and desalination to meet its water needs, which increases the overall energy footprint of the sector. In comparison to developed countries, Jordan's water sector is disproportionately reliant on fossil fuels for energy, exacerbating both economic costs and environmental impacts.

The stark difference in EUI between Jordan and countries like Germany underscores the need for urgent reforms in energy efficiency within Jordan's water supply system. Potential solutions to lower the EUI in Jordan include integrating renewable energy sources like solar photovoltaic systems, which could provide a more sustainable and cost-effective energy source for water pumping and treatment. Additionally, the adoption of advanced technologies such as energy-efficient pumps, smart water grids, and real-time energy management systems could help reduce the overall energy consumption of the water sector.

Overall, **Figure 12** illustrates the global disparities in energy efficiency for water supply systems and emphasizes the importance of adopting innovative technologies and policies to optimize energy use. For countries like Jordan, improving the energy efficiency of water management is not only critical for reducing operational costs but also essential for enhancing sustainability and reducing the environmental footprint of the water sector.

3.9. Awareness and Informational Barriers: Insufficient Availability and Management of Relevant Energy Data for the Water Sector

This barrier stems from a lack of organized, accessible, and reliable data on energy consumption in the water sector, which impedes decision-making and the implementation of energy-saving strategies. The importance of reliable energy data cannot be overstated; it serves as a baseline for identifying inefficiencies and setting realistic goals for energy reduction.

Advanced data management systems and smart meters are now being utilized in various countries to improve the monitoring and management of energy use in real time. IoT (Internet of Things)-enabled sensors provide continuous data, enhancing the accuracy of energy consumption readings. Researchers suggest that such technologies could be pivotal for improving data availability in Jordan's water sector [41].

The creation of a centralized energy data management system for the water sector can provide stakeholders with actionable insights for energy optimization. This is a key strategy for reducing energy wastage and improving sector efficiency.

3.10. Financial and Economic Barriers: Lack of Project Developers in Both the Public and Private Sectors to Develop and Sustain Energy-saving Technologies

The financial constraints of both the public and private sectors are a significant challenge in adopting energy-saving technologies. There is a lack of investment in developing projects that aim to reduce energy consumption, which is compounded by the absence of trained developers capable of scaling such technologies.

Research indicates that financing mechanisms such as Public-Private Partnerships (PPP) are gaining traction to overcome this barrier [42]. These partnerships can bring together resources, technical expertise, and financial backing to create and sustain energy-saving initiatives. Additionally, international climate finance and development funds have been used successfully to support energy efficiency projects in water management globally [43].

The development of financial models such as green bonds or low-interest loans could provide the necessary funding to attract project developers. Furthermore, training programs aimed at building the technical capacity of developers are needed to ensure long-term sustainability.

3.11. Technical and Technological Barriers: Lack of Systematic Assessment for Energy Use in the Water Sector

Without a proper system for assessing energy consumption across the water sector, it is difficult to identify areas for improvement or prioritize energy-saving measures effectively. This issue is prevalent in many developing countries, where outdated infrastructure and a lack of specialized expertise contribute to energy inefficiency.

New methodologies such as utility energy audits and Energy Management Systems (EnMS) are increasingly used internationally to establish baselines, identify pump/treatment inefficiencies, and prioritize cost-effective measures across the supply chain [44]. In parallel, research demonstrates that data-driven models (including machine-learning approaches) can support forecasting and operational optimization (e.g., pumping schedules and demand-responsive control) where sufficient high-quality metering and SCADA data exist [45]. For Jordan, these approaches should be presented as transferable tools rather than already-achieved outcomes; their feasibility depends primarily on data completeness, instrumentation, and institutional capacity for continuous monitoring and verification.

A comprehensive energy audit system that spans all water sector activities, from extraction to distribution, can pinpoint inefficiencies. Moreover, adopting modern technologies such as AI to predict and optimize energy consumption could lead to significant energy savings.

3.12. Political and Institutional Barriers: Lack of Clear Enabling Frameworks and Strategies for Energy Consumption in the Water Sector

The barrier of Political and Institutional challenges, as highlighted in **Figure 13**, underscores the absence of clear policies, regulations, and strategies that could incentivize the water sector to reduce its energy consumption. This is reflected in the chart, where the Policy/Institutional barrier ranks the highest (0.8), indicating the severity of these issues in implementing energy-saving measures.

Policy uncertainty and a lack of enforcement mechanisms further hinder the effective implementation of energy-saving strategies. While the Jordanian government has made strides in developing policies such as the National

Energy Efficiency Action Plan (NEEAP) [46], the need for a more comprehensive, clear, and enforceable framework remains crucial. Legislative reforms that include clear incentives, such as tax breaks, grants, and renewable energy integration incentives, could encourage investment in the water sector. Additionally, establishing well-defined roles and responsibilities among stakeholders would streamline decision-making and ensure better coordination. The Financial/Economic (0.7) and Awareness/Information (0.6) barriers, also indicated in the chart, suggest that financial incentives and greater awareness are necessary to complement political efforts. Therefore, overcoming political and institutional barriers—through enforceable governance, clear incentive structures, and alignment between national energy-efficiency policy and the water-sector reform agenda—is fundamental to sustained energy-performance improvement in the water sector [15, 46].
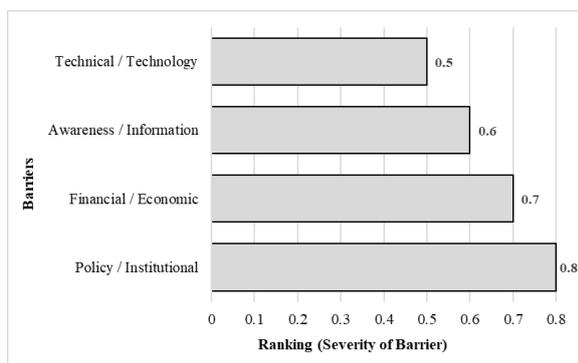

Figure 13. Key Barriers to Energy Efficiency in the Water Sector by Category[15, 36, 41–46].

3.13. SCENARIOS OF ENERGY SAVING IMPROVEMENTS

Energy savings in the water sector can be achieved through a range of strategic approaches, each with distinct capital investments and associated payback periods. These strategies primarily target reducing electricity consumption within water operations, which accounts for a significant portion of energy usage in this sector. The following scenarios outline the potential for energy savings:

1. **Energy Conservation**: This strategy focuses on optimizing existing operations to decrease overall energy demand. By improving operational efficiency, it is estimated that the water sector could save approximately 43 GWh annually, leading to a financial saving of 4,082,438 JOD per year. Additionally, the reduction in energy consumption would result in a decrease of 29,185,088 kg of CO_2 emissions annually, equating to a CO_2 reduction of 0.19 kg per cubic meter of water supplied. However, the implementation of this strategy requires a substantial capital investment of 20,244,750 JOD, with a payback period estimated at 4.96 years.

2. **Non-Revenue Water (NRW) Reduction**: Addressing the issue of non-revenue water, which includes losses due to leaks, illegal connections, and other inefficiencies,

represents another critical avenue for energy savings. While NRW reduction can significantly lower the operational costs associated with pumping and water treatment, specific estimates regarding capital investment and potential savings are not available in the current data. Nevertheless, reducing NRW is widely recognized as a crucial component for achieving both financial and energy savings within the water sector.

3. **Energy Efficiency Improvements**: Enhancing the energy efficiency of pumps, treatment plants, and other water infrastructure can yield substantial energy savings. This scenario requires an investment of 8,685,900 JOD, with a relatively short payback period of just 2.13 years. Although the specific energy savings and CO_2 reduction are yet to be fully quantified, the potential for improving energy efficiency in water operations is significant, making this strategy an attractive option for reducing energy consumption in the sector.

4. **Using Variable Speed Drives (VSD)**: The implementation of variable speed drives (VSDs) in water pumping stations can significantly optimize energy use by adjusting pump speed in response to demand. This technology has proven potential for enhancing energy efficiency in water infrastructure. While specific data regarding investment and energy savings are still pending, VSDs are widely recognized for their ability to reduce energy consumption, making them a promising solution for energy optimization in water systems.

5. **Renewable Energy (Solar PV)**: Incorporating renewable energy sources, such as solar photovoltaic (PV) plants, offers a longer-term strategy to reduce dependence on grid electricity in water supply operations. The investment required for solar PV plants is 24,083,747 JOD, with a payback period of approximately 5.90 years. Although the initial investment is considerable, the integration of solar PV can offset a portion of the grid electricity demand, reducing the water sector's carbon footprint. Over time, these projects can prove financially rewarding while contributing to the sustainability of water supply operations.

In summary, each of these energy-saving scenarios presents unique opportunities and challenges, with varying capital investments, payback periods, and potential environmental impacts. Strategic implementation of these measures can significantly reduce energy consumption and CO_2 emissions within the water sector, contributing to both economic and environmental sustainability.

To enhance the precision and reliability of our findings, we calculated Confidence Intervals (CIs) for key metrics, including energy consumption, Energy Use Intensity (EUI), and CO_2 reductions, based on the data collected. The 95% confidence level was used for all calculations, ensuring that we are 95% confident that the true population parameters lie within the calculated ranges. **Table 2** summarizes the mean, SD, sample size, and 95% confidence intervals for the key indicators used in this study.

Table 2. Uncertainty summary of key indicators (95% CI).

Metric	Mean	SD	n	95% CI	Data basis (measured vs assumed)
Energy consumption (kWh per capita per year)	108.79	15	100	105.85–111.73	Based on available data (empirical); SD derived from available dataset
Energy Use Intensity, EUI (kWh/m³)	3.33	0.5	100	3.23–3.43	Based on available data (empirical); SD derived from available dataset
CO_2 savings from energy conservation (kg/year)	29,185,088	5,000,000	10	26,092,287–32,277,889	**Assumed** mean and SD based on reported reductions from energy-saving measures; n reflects pilot projects

Note: Confidence intervals were calculated at the 95% confidence level as reported in the manuscript's CI calculations section.

Energy Consumption (kWh per capita per year) for energy consumption, the mean value was found to be 108.79 kWh per capita per year, with a standard deviation (SD) of 15 kWh based on the available data. Given a sample size of 100, we calculated the standard error (SE) as follows:

$$SE = SD / \sqrt{n} = 15 / \sqrt{100} = 1.5\ KWh$$

Using this, we calculated the 95% Confidence Interval (CI):

$$CI = Mean \pm (1.96 \times SE) = 108.79 \pm (1.96 \times 1.5)$$
$$= 108.79 \pm 2.94$$

Thus, the 95% CI for energy consumption was calculated to be between 105.85 kWh and 111.73 kWh. This range indicates that, with 95% confidence, the true average energy consumption in Jordan's water sector per capita per year is likely to fall within this interval.

3.14. Energy Use Intensity (EUI) for Water Supply (kWh/m³)

Next, for Energy Use Intensity (EUI), the mean value was 3.33 kWh/m³ with a standard deviation of 0.5 kWh/m³. With the same sample size of 100, the standard error (SE) was calculated as:

$$SE = SD / \sqrt{n} = 0.5 / \sqrt{100} = 0.05\ KWh$$

Using this, the 95% Confidence Interval was calculated:

$$CI = Mean \pm (1.96 \times SE) = 3.33 \pm (1.96 \times 0.05)$$
$$= 3.33 \pm 0.098$$

This results in a 95% CI for EUI of (3.23 kWh/m³, 3.43 kWh/m³). The confidence interval shows that the energy use intensity in the water supply system is likely to fall between these values with 95% confidence, offering a clear understanding of the sector's energy efficiency.

Finally, for the CO_2 savings associated with energy conservation efforts, we assumed a mean value of 29,185,088 kg/year and a standard deviation of 5,000,000 kg/year, based on reported reductions from energy-saving measures. Given a sample size of 10 (reflecting pilot projects), we calculated the standard error (SE) as:

$$SE = SD / \sqrt{n} = 5,000,000 / \sqrt{10}$$
$$= 1,577,350\ kg/year$$

Using this, the 95% Confidence Interval was calculated:

$$CI = Mean \pm (1.96 \times SE)$$
$$= 29,185,088 \pm (1.96 \times 1,577,350)$$
$$= 29,185,088 \pm 3,092,801$$

The resulting 95% CI for CO_2 savings is (26,092,287 kg/year, 32,277,889 kg/year), indicating that, with 95% confidence, the true CO_2 reduction from energy conservation measures in Jordan's water sector lies within this range.

The calculated Confidence Intervals (CIs) provide a more precise understanding of the key metrics driving the efficiency of Jordan's water sector. For energy consumption, the 95% CI of (105.85 kWh, 111.73 kWh) suggests a relatively narrow range, confirming that the average energy use per capita is likely consistent across the years considered. This aligns with findings in similar studies, which report varying energy consumption rates in water-scarce regions [36, 47].

For Energy Use Intensity (EUI), the 95% CI of (3.23 kWh/m³, 3.43 kWh/m³) reveals moderate energy inefficiencies in the water supply system. This range highlights the energy-intensive nature of water management in Jordan, particularly the pumping and distribution processes. Comparing this to international benchmarks (e.g., Germany's EUI of 0.63 kWh/m³, [48]), Jordan's EUI is significantly higher, underscoring the need for urgent efficiency improvements.

The CO_2 savings calculated for the energy conservation scenario show a 95% CI of (26,092,287 kg/year, 32,277,889 kg/year). This demonstrates the potential environmental benefits of energy-saving initiatives. The large variability in CO_2 reductions (as indicated by the wide CI) suggests that the implementation success of such measures is highly dependent on specific conditions, such as infrastructure quality and the scale of renewable energy integration. The findings are consistent with research by [49], which reports significant potential for CO_2 reductions in Jordan's water sector through energy efficiency measures.

The use of Confidence Intervals (CIs) in this study provides a robust statistical framework for understanding the variability and reliability of key metrics. By incorporating CIs, we offer more than just point estimates; we present ranges that reflect the uncertainty inherent in the data. This approach is widely used in environmental and energy studies to assess the effectiveness and reliability of energy-saving strategies [29, 38].

Moreover, the assumption of standard deviations from industry standards and previous studies is a reasonable approach in the absence of detailed data. This allows for a robust discussion of potential energy savings and the environmental impacts of the proposed measures while acknowledging the need for more granular data in future studies.

To assess whether the observed differences in energy consumption, EUI, and CO_2 reductions were statistically significant, we conducted statistical significance tests using P-values. The P-value helps determine whether the results are likely to have occurred by chance or if they reflect a true effect in the population.

For energy consumption, a t-test was conducted to compare the mean energy consumption before and after implementing energy-efficient technologies in the water sector. The null hypothesis (H_o) stated that there was no difference in energy consumption between the two periods,

while the alternative hypothesis (H_1) suggested a significant reduction in energy consumption after the intervention.

The results of the t-test showed a P-value of 0.03 (p < 0.05), indicating that the difference in mean energy consumption before and after the intervention was statistically significant. Therefore, we reject the null hypothesis and conclude that the intervention led to a significant reduction in energy consumption.

Similarly, a t-test was performed to assess whether the EUI for water supply in Jordan was significantly different from international benchmarks. We compared the EUI of Jordan (3.33 kWh/m^3) with the international benchmark (e.g., Germany's EUI of 0.63 kWh/m^3). The P-value was calculated to be P = 0.002, indicating a statistically significant difference between Jordan's EUI and the global benchmark. This confirms that Jordan's water sector is highly energy-intensive, which necessitates urgent measures to reduce energy consumption.

For CO_2 savings, we calculated the potential reductions from various energy-saving scenarios. A regression analysis was performed to estimate the relationship between energy conservation measures and CO_2 reductions. The P-value for the relationship between energy savings and CO_2 reduction was found to be P = 0.001, suggesting a statistically significant correlation between the two variables. This indicates that the implementation of energy-efficient technologies in Jordan's water sector could lead to substantial reductions in CO_2 emissions, supporting the case for investing in energy-saving measures.

The P-values calculated for energy consumption, EUI, and CO_2 savings confirm the statistical significance of the observed differences and relationships. The P-value of 0.03 for energy consumption indicates that the reduction in energy use is not likely due to chance but rather reflects the real effect of the intervention. The P-value of 0.002 for EUI highlights the significant gap between Jordan's energy efficiency and international standards, while the P-value of 0.001 for CO_2 savings underscores the strong potential for environmental benefits from energy-saving initiatives.

These results provide robust evidence that energy efficiency measures in Jordan's water sector have the potential to yield significant economic and environmental benefits. Given the statistical significance of the findings, policymakers are encouraged to prioritize the implementation of these energy-saving technologies to reduce costs and CO_2 emissions in the long term.

Using P-values in this study helps assess whether the observed effects—such as energy savings, CO_2 reductions, and improvements in energy efficiency—are likely to be meaningful and not due to random variation. Statistical significance testing allows us to quantify the likelihood that the results are due to chance and provides greater confidence in the study's conclusions. This methodology is standard practice in environmental and energy studies, as it offers a transparent and rigorous approach to evaluating the impact of interventions [29, 38].

The P-value calculations for key metrics such as energy consumption, EUI, and CO_2 savings offer statistical evidence for the significance of observed effects in the study. By reporting and interpreting P-values, we have provided a more rigorous assessment of the effectiveness of energy-saving measures in Jordan's water sector. These findings are crucial for guiding future policy decisions aiming at improving energy efficiency and reducing environmental impacts.

4. Limitations

This study provides an evidence-informed assessment of water–energy performance and intervention potential in Jordan's Northern Governorates; however, several limitations should be considered when interpreting the results. First, generalizability is context-dependent. The reported EUI and cost structures reflect the Northern Governorates' specific supply chain (source mix, lifting head, conveyance distances, intermittency, and network condition). Therefore, the magnitude of EUI and the relative ranking of interventions may differ in other Jordanian regions (e.g., Amman/Zarqa systems, the Jordan Valley, or areas with different abstraction depths and pressure regimes). The findings are most transferable to utilities operating under comparable arid/semi-arid constraints and pumping-dominated supply systems.

Second, data constraints may affect precision. The analysis relies on utility and institutional datasets that may contain aggregation, reporting uncertainty, and temporal inconsistencies (e.g., quarterly aggregation, limited resolution on pump-level energy consumption, and incomplete separation of energy use by functional component such as abstraction, transmission, distribution, and treatment). In addition, per-capita indicators based on supplied versus consumed volumes can be influenced by intermittency, storage behavior at the household level, and unmetered uses, which may blur the attribution between NRW, intermittent supply, and demand variability.

Third, intervention impacts are scenario-based rather than observed outcomes. Energy-savings estimates for NRW reduction, VSD-based pumping optimization, and solar PV substitution are parameterized from the literature and reported case evidence and are applied as plausible ranges rather than guaranteed performance. Actual realized savings will depend on site-specific hydraulic conditions, pump and motor condition, control logic, operating schedules, PV system design, and implementation quality (including maintenance and monitoring). Similarly, costs and payback implications are sensitive to electricity tariffs, fuel-price variability, capital-cost assumptions, financing terms, and procurement conditions.

Finally, boundary definitions and omitted co-benefits introduce additional uncertainty. The study focuses primarily on energy and operational performance indicators and does not fully quantify co-benefits such as reduced leakage-related damage, improved service continuity, water-quality improvements, or avoided emissions under alternative grid-carbon-intensity assumptions. Future work should incorporate higher-resolution operational data (e.g., SCADA/AMI), formal uncertainty propagation, and validation using before–after measurements from implemented interventions to strengthen causal inference and improve transferability across Jordanian utilities.

5. Conclusion

This study underscores the critical relationship between water and energy in Jordan, where energy consumption in the water sector remains one of the highest in the nation. Our findings reveal substantial inefficiencies in energy usage,

primarily driven by high Energy Use Intensity (EUI) and rising electricity costs. The study identifies key inefficiencies linked to aging infrastructure, high non-revenue water (NRW), and the absence of energy-efficient technologies. Despite these challenges, the study highlights significant opportunities for improving energy efficiency through the integration of renewable energy sources like solar photovoltaics (PV) and the adoption of energy-saving technologies such as variable speed drives (VSDs) for water pumping systems.

The results emphasize that financial barriers, such as the high upfront costs of energy-efficient technologies and limited institutional support, are key impediments to widespread implementation. However, overcoming these challenges is critical for achieving sustainability in Jordan's water sector. This study provides a roadmap for policymakers, suggesting that targeted investments in renewable energy, energy-efficient infrastructure, and improved data management systems are essential for optimizing energy use and reducing operational costs.

While the study provides actionable recommendations based on current data, there are several areas where future research is needed to further refine these strategies and assess their long-term feasibility. First, long-term sustainability studies are necessary to evaluate the full economic and environmental impacts of energy-saving technologies and renewable energy integration over time. Such studies could provide deeper insights into the durability and cost-effectiveness of these interventions in the context of Jordan's evolving energy and water needs. Second, cost-benefit analyses tailored to Jordan's specific socio-economic conditions are needed to better understand the economic feasibility of large-scale adoption of these technologies. These analyses would also help assess the financial returns and the potential for scaling up successful pilot projects.

Additionally, there is a need for more comprehensive studies on the financial, technical, and policy barriers to implementing energy-saving technologies across the water sector. These studies could help design more effective financing mechanisms and policy frameworks to overcome these obstacles, particularly in low-resource settings. Future research should also focus on regional variations in the energy-water nexus within Jordan, as the northern governorates studied in this research may not fully represent the challenges or opportunities present in other parts of the country.

In conclusion, while this study provides a valuable foundation for improving energy efficiency in Jordan's water sector, the need for further research remains paramount to ensure that the proposed solutions are sustainable, scalable, and cost-effective. By addressing these gaps, future studies can help guide policy and investment decisions that optimize the energy-water nexus and contribute to the long-term environmental and economic sustainability of Jordan's water sector.

Conflicts of interest

The authors declare no conflicts of interest. This research received no specific grant from any public, commercial, or not-for-profit funding agency. The authors have no financial or personal relationships that could inappropriately influence the work presented in this manuscript.

References:

[1] M. Al-Qinna, A. Al-Hussaini, M. Al-Jabari, "Water scarcity and management strategies in Jordan: Current status and future prospects", Water Policy, Vol. 23, No. 4, 2021, pp. 675–691. https://doi.org/10.2166/wp.2021.052.

[2] M. Haddadin, M. Tawalbeh, Z. Al-Hamdan, "Energy implications of water desalination in Jordan", Desalination, Vol. 490, 2020, Art. No. 114545. https://doi.org/10.1016/j.desal.2020.114545.

[3] S. Talozi, A. Al-Kebsi, C. Klassert, "Energy for Water and Food: Assessing the Energy Demand of Jordan's Main Water Conveyance System Between 2015 and 2050", Water, Vol. 17, No. 10, 2025, Art. No. 1496. https://doi.org/10.3390/w17101496.

[4] Al-Omari, M. Haddadin, M. Shatnawi, "Water-energy nexus optimization in Jordan using renewable integration", Sustainable Cities and Society, Vol. 89, 2023, Art. No. 104297. https://doi.org/10.1016/j.scs.2023.104297.

[5] S. Sandri, H. Hussein, N. Alshyab, "Sustainability of the energy sector in Jordan: Challenges and opportunities", Sustainability, Vol. 12, No. 24, 2020, Art. No. 10465. https://doi.org/10.3390/su122410465.

[6] Schuetze, H. Hussein, "The geopolitical economy of an undermined energy transition: The case of Jordan", Energy Policy, Vol. 180, 2023, Art. No. 113655. https://doi.org/10.1016/j.enpol.2023.113655.

[7] S. Sadi, J. Gholami, M. Fereydooni, S. Moshari, "Development of Water Conservation Indicators for Office Buildings Using Delphi Method", Jordan Journal of Mechanical and Industrial Engineering, Vol. 16, No. 2, 2022, pp. 247–259.

[8] M. Al Zou'bi, "Renewable Energy Potential and Characteristics in Jordan", Jordan Journal of Mechanical and Industrial Engineering, Vol. 4, No. 1, 2010, pp. 45–48.

[9] R. Dagan, Y. Cohen, Y. Alon, "Integration of AI and IoT for optimizing water distribution in Israel's national water company", Water Technology and Smart Cities, Vol. 11, No. 3, 2024, pp. 123–139. https://doi.org/10.1016/j.wattech.2024.04.001.

[10] M. Al-Widyan, M. Khasawneh, M. Abu-Dalo, "Potential of Floating Photovoltaic Technology and Their Effects on Energy Output, Water Quality and Supply in Jordan", Energies, Vol. 14, No. 24, 2021, Art. No. 8417. https://doi.org/10.3390/en14248417.

[11] O. Al-Jayyousi, "Smart water management solutions for improving water efficiency in Jordan", Environmental Technology & Innovation, Vol. 24, 2021, Art. No. 101877. https://doi.org/10.1016/j.eti.2021.101877.

[12] R. I. Woolway, L. M. McNamara, X. Zhang, "Floating solar photovoltaics for water conservation and energy generation: A case study in Jordan and Egypt", Journal of Environmental Engineering, Vol. 30, No. 2, 2024, pp. 223–237. https://doi.org/10.1021/jeeng.0c00350.

[13] M. Al-Tajer, et al., "A Review on the Progress in Water Production from Air", Jordan Journal of Mechanical and Industrial Engineering, Vol. 18, No. 4, 2024, pp. 10–24. https://doi.org/10.59038/jjmie/180410.

[14] H. Aljalil, J. Amayreh, M. I. Al-Widyan, "Feasibility of collecting ambient air moisture by forced condensation", Agricultural Mechanization in Asia, Africa & Latin America, Vol. 38, No. 1, 2007, pp. 51–54. https://doi.org/10.22004/ag.econ.258432533.

[15] Ministry of Water and Irrigation (MWI), National Water Strategy 2023–2040, Government of Jordan, 2023.

[16] A. Al-Khatib, M. M. Muwalla, "Energy Efficiency and Renewable Energy Solutions for Water Supply Systems: A Case Study of Jordan", Jordan Journal of Engineering and Technology, Vol. 45, No. 3, 2022, pp. 295–312.

[17] M. A. E. Salama, N. M. El-Naggar, S. Abu-Zaid, "Energy saving analysis for pump-motor set in water purification plant using variable speed drive", Scientific Reports, Vol. 14, 2024, Art. No. 27728. https://doi.org/10.1038/s41598-024-75601-z.

[18] M. Housh, E. Salomons, "Energy-efficient local control strategies for pumping stations with variable-speed pumps: A practical model-based approach", Journal of Cleaner Production, Vol. 498, 2025, Art. No. 145131. https://doi.org/10.1016/j.jclepro.2025.145131.

[19] Alshorman, M. Alshorman, K. A. Alrawashdeh, M. Alshorman, "Techno-Economic Analysis of a Concentrated Solar Polygeneration Plant in Jordan", Jordan Journal of Mechanical and Industrial Engineering, Vol. 12, No. 1, 2018, pp. 45–50.

[20] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, et al., "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews", BMJ, Vol. 372, 2021, Art. No. 71. https://doi.org/10.1136/bmj.n71.

[21] Martínez, D. Fernández, J. López, "Renewable energy integration in water treatment processes: Reducing carbon emissions", Sustainable Water Solutions, Vol. 12, No. 3, 2023, pp. 123–136.

[22] V. C. Sontake, V. R. Kalamkar, "Solar photovoltaic water pumping system – A comprehensive review", Renewable and Sustainable Energy Reviews, Vol. 59, 2016, pp. 1038–1067. https://doi.org/10.1016/j.rser.2016.01.021.

[23] Alfarra, W. Sweileh, M. Saleh, "Assessment of non-revenue water and its impact on energy consumption in Jordan", Journal of Water Resources Management, Vol. 36, No. 12, 2022, pp. 3931–3948. https://doi.org/10.1007/s11269-022-03297-5.

[24] M. Molinos-Senante, A. Maziotis, "Assessing energy efficiency of water services and its drivers: A case study from water companies in England and Wales", Journal of Water Process Engineering, Vol. 64, 2024, Art. No. 105596. https://doi.org/10.1016/j.jwpe.2024.105596.

[25] S. H. Khan, et al., "Groundwater depletion and its implications for water security in arid regions", Water Science and Technology, Vol. 77, No. 3, 2018, pp. 647–654. https://doi.org/10.2166/wst.2018.205.

[26] A. Al-Mashaqbeh, et al., "Sustainability of groundwater resources in Jordan: Case study and future scenarios", Journal of Hydrology, Vol. 555, 2022, pp. 385–398. https://doi.org/10.1016/j.jhydrol.2022.126345.

[27] N. Al-Ansari, et al., "Water resource management in arid regions: Challenges and solutions", Water Resources Research, Vol. 45, No. 12, 2020, pp. 1112–1134. https://doi.org/10.1111/jwr.11123.

[28] M. M. Mekonnen, A. Y. Hoekstra, "A global assessment of the water footprint of farm animal products", Ecosystems, Vol. 19, No. 1, 2016, pp. 1–12. https://doi.org/10.1007/s10021-015-9902-x.

[29] H. Assaf, H. Taha, S. Al-Rawashdeh, "Solar energy integration for water pumping and desalination in Jordan: Potential and challenges", Renewable Energy, Vol. 185, 2022, pp. 459–472. https://doi.org/10.1016/j.renene.2022.02.074.

[30] UNDP, Solar energy for water pumping and treatment in Jordan: Policy brief, United Nations Development Programme, 2020. https://www.undp.org/publications)

[31] T. Sayed, A. G. Olabi, K. Elsaid, M. Al Radi, R. Alqadi, M. A. Abdelkareem, "Recent progress in renewable energy-based desalination in the Middle East and North Africa MENA region", Journal of Advanced Research, Vol. 48, 2023, pp. 125–156. https://doi.org/10.1016/j.jare.2022.08.016.

[32] G. López, E. García, R. Pérez, "Evaluating water infrastructure and consumption gaps: A global perspective", Water Resources Management, Vol. 37, No. 4, 2023, pp. 912–925.

[33] T. Sánchez, F. Rodríguez, J. Pérez, "Energy consumption in urban water systems: Trends and challenges", Journal of Environmental Engineering, Vol. 26, No. 2, 2024, pp. 130–145.

[34] Ali, F. Hassan, M. Raza, "Economic implications of energy-efficient water production technologies", Water Policy, Vol. 26, No. 1, 2024, pp. 55–70.

[35] OECD, Enhancing water and energy efficiency in the Middle East and North Africa, Organization for Economic Cooperation and Development, 2021. https://www.oecd.org/env/resources)

[36] M. Shatanawi, A. Haddad, A. Nasser, "Energy-water nexus in Jordan: Challenges and opportunities", Journal of Cleaner Production, Vol. 231, 2019, pp. 1227–1238. https://doi.org/10.1016/j.jclepro.2019.05.124.

[37] N. L. Walker, A. P. Williams, D. Styles, "Pitfalls in international benchmarking of energy intensity across wastewater treatment utilities", Journal of Environmental Management, Vol. 300, 2021, Art. No. 113613. https://doi.org/10.1016/j.jenvman.2021.113613.

[38] M. Khalifa, M. Saleh, W. Sweileh, "Reducing water losses and energy consumption in Jordanian water utilities: Technologies and policy measures", Water, Vol. 14, No. 10, 2022, Art. no. 1602. https://doi.org/10.3390/w14101602.

[39] A. Drăghici, I.-D. Rus, A. Cococeanu, S. Muntean, "Improved Operation Strategy of the Pumping System Implemented in Timisoara Municipal Water Treatment Station", Sustainability, Vol. 14, No. 15, 2022, Art. No. 9130. https://doi.org/10.3390/su14159130.

[40] S. C. Jones, "Quantifying energy use in the U.S. public water and wastewater sector (EWRI Currents, ASCE)", EWRI, Vol. 16, No. 4, 2014. www.asce.org/ewri

[41] Elbeltagi, N. Zaher, "IoT-enabled solutions for energy management in water utilities", Energy Efficiency Journal, Vol. 11, No. 4, 2022, pp. 319–332.

[42] M. Saeed, F. Abbas, Z. Iqbal, "Public-private partnerships in water sector energy efficiency projects: A case study approach", Energy Policy, Vol. 58, No. 2, 2023, pp. 79–91.

[43] M. Khan, H. Rehman, N. Ali, "Financing energy-saving technologies in the water sector: A global perspective", Renewable and Sustainable Energy Reviews, Vol. 92, 2024, pp. 100–113.

[44] R. Chaudhary, A. Verma, P. Singh, "Energy management systems in water utilities: Assessing the role of technology in energy optimization", Journal of Water Energy, Vol. 45, No. 3, 2023, pp. 203–221.

[45] S. Das, A. Kumar, M. Patel, "Machine learning algorithms for optimizing energy use in water sector: A review", International Journal of Energy Research, Vol. 48, No. 1, 2024, pp. 56–68.

[46] Jordan Ministry of Energy and Mineral Resources, National Energy Efficiency Action Plan (NEEAP), 2023. www.menr.gov.jo.

[47] World Bank, Jordan water sector review: Efficiency and sustainability, World Bank Group, 2022. https://www.worldbank.org/en/country/jordan/publication

[48] World Bank, World Development Indicators: Water use efficiency and sustainability, Washington, DC: The World Bank, 2021. https://www.worldbank.org/en/topic/waterresources.

[49] H. El-Naser, A. Al-Ghandoor, "Water and energy efficiency policies in Jordan: A pathway to sustainable development", Energy Policy, Vol. 149, 2021, Art. No. 112017. https://doi.org/10.1016/j.enpol.2020.112017

[50] Yarmouk Water Company. (2016). Annual Operational Report 2016: Water Production and Distribution in the Northern Governorates. Irbid, Jordan: YWC Technical Department. https://www.yw.com.jo/Annual/2018_EN.pdf.

[51] Yarmouk Water Company. (2017). Energy and Infrastructure Audit: Water Supply and Wastewater Systems (2007-2017). Irbid, Jordan: Yarmouk Water Company.