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The Significance of Renewable Energy in a Water-Scarce World: A Case Study of Jordan

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ABSTRACT: Amidst a global water crisis, Jordan is an example of extreme water scarcity. With one of the world's lowest per capita freshwater availability, Jordan's growing population and limited resources create a dangerous balance. This research paper investigates into the vital role of renewable energy in addressing Jordan's water woes and proposes a sustainable path for the future. Through a comprehensive case study, integrating renewable energy and water desalination in arid regions represents a promising pathway for sustainable water management and environmental conservation. By harnessing abundant renewable resources, arid regions can address their pressing water needs, mitigate climate change, and reduce dependence on non-renewable energy sources. Overcoming economic barriers and optimizing technology will be crucial in fully unlocking the potential of this innovative approach for a water-secure and environmentally conscious future.

KEYWORDS: Renewable energy, water scarcity, desalination, Jordan, freshwater

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Introduction

Global water scarcity has far-reaching consequences, affecting developed and developing nations. This pressing issue jeopardizes human rights and threatens economic growth and social stability (Mishra & Tushaus, 2022; Shemer et al., 2023). Climate change acts as a compounding factor, intensifying the challenges associated with water scarcity. The increased frequency and severity of extreme weather events, alterations in the water cycle, and depletion of water resources contribute to the growing crisis (Mahato et al., 2022). Importantly, water scarcity extends beyond a mere quantity problem and manifests as a quality issue. Polluted return flows further degrade water quality, exacerbating the overall problem (Guarino, 2017). This dual challenge of quantity and quality has profound implications for public health. The lack of access to clean water sources results in severe health issues, with contaminated drinking water causing diseases such as diarrhea, leading to significant mortality rates (Van Vliet et al., 2021).

Addressing water scarcity demands a multifaceted approach. Utilizing alternative water sources, such as desalination and wastewater reclamation, is crucial. Additionally, improving water catchment and harvesting technologies can enhance water availability. Pollution control measures are essential to safeguard water quality. Implementing these actions necessitates coordinated efforts, including centralized governance, educational campaigns, infrastructure development, and transboundary water cooperation. Desalination and wastewater reclamation technologies offer promising solutions by tapping into non-traditional water sources. Advancements in these technologies can provide a sustainable means of meeting water demand in water-scarce regions. Simultaneously, improving water catchment and harvesting technologies helps maximize the efficient use of available water resources.

Crucially, pollution control measures play a pivotal role in preserving water quality. Mitigating industrial, agricultural, and domestic pollution helps prevent further degradation of water sources. Centralized governance is essential for formulating and enforcing regulations to control pollution effectively. Educational campaigns are vital components of any strategy to address water scarcity. Raising awareness about responsible water usage, conservation practices, and the importance of pollution prevention fosters a collective sense of responsibility. Infrastructure development, including establishing water treatment facilities and distribution networks, ensures reliable access to clean water.

Moreover, addressing water scarcity often requires collaboration across borders. Transboundary water cooperation is essential, especially in regions where water resources span multiple countries. Joint efforts can lead to more effective and sustainable water management practices, benefiting all involved nations.

Potential solutions to global water scarcity include infrastructure investment, expansion of clean water technologies such as desalination and treated wastewater reuse, and the application Of Adaptive Inner-Basin Water Allocation Measures (AIWAM) (He et al., 2021; Huang et al., 2021). Infrastructure investment can help relieve water scarcity in more than two-thirds of water-scarce cities, but environmental trade-offs must be considered (Salehi, 2022). Expanding desalination and treated wastewater can significantly reduce water scarcity levels and the number of people affected, especially in Asia. However, side effects such as brine and energy demand must be considered (Endo et al., 2018). Applying AIWAM can mitigate water scarcity for nonagricultural sectors but may increase water scarcity for agriculture in upstream areas. These potential solutions provide useful information for developing adaptation strategies toward sustainable water management.

Mitigating global water scarcity necessitates a holistic approach encompassing technological innovations, regulatory frameworks, educational initiatives, and international cooperation. By implementing a comprehensive strategy, the world can ensure equitable access to clean water, promote sustainable development, and safeguard communities' well-being worldwide. A comprehensive understanding of global water scarcity involves recognizing the interconnected nature of water quantity and quality, understanding the dynamic changes in terrestrial water storage, acknowledging historical trends, addressing monthly water scarcity challenges, and grappling with the consequences of increased water consumption over the 20th century. Addressing these aspects collectively is essential for formulating effective and sustainable water management strategies globally.

Water scarcity is a complex and widespread global challenge arising from both insufficient water quantity and compromised water quality. Water scarcity is not only about the physical availability of water but also about its suitability for various uses. Including water quality in assessments significantly alters the perception of the problem. The integration of water quality concerns raises the percentage of the world's population suffering from severe water scarcity from 30% to 40%. This highlights the critical importance of considering both quantitative and qualitative aspects in addressing global water challenges (Van Vliet et al., 2021).

The observed changes in terrestrial water storage from 2002 to 2016 provide crucial insights into the dynamic nature of global freshwater availability. These changes indicate shifts in the distribution and volume of water resources worldwide. Unsustainable groundwater consumption, driven by agricultural, industrial, and domestic needs, significantly alters terrestrial water storage. Additionally, climate change contributes to these changes, affecting precipitation patterns, evaporation rates, and overall hydrological cycles (Rodell et al., 2018). Understanding these dynamics is essential for developing adaptive strategies to manage water resources sustainably.

A historical analysis reveals that water shortages began to escalate around 1900. This period marks a crucial turning point in the relationship between human populations and water resources. By 2005, 35% of the world's population resided in areas with chronic water shortages (Kummu et al., 2010). Historical trends help contextualize the contemporary water crisis, providing insights into the long-term impact of human activities and environmental changes on water availability.

The statistic that two-thirds of the global population faces severe water scarcity at least 1 month per year underscores the recurrent and widespread nature of the problem. This monthly cycle of stress on water resources has significant implications for various sectors, including agriculture, industry, and households. Moreover, the disproportionate impact on countries like India and China emphasizes the need for targeted interventions in regions experiencing heightened water stress (Mekonnen & Hoekstra, 2016).

The fourfold increase in water consumption during the 20th century signifies a substantial surge in global water demand. This surge is driven by population growth, urbanization, industrialization, and changing lifestyles. The consequence is a notable increase in the percentage of the global population living under water scarcity conditions, rising from 14% to 58% (Kummu et al., 2016). Addressing this challenge requires a holistic approach that combines water conservation measures, technological innovation, and sustainable management practices.

Renewable Energy and Desalination

The confluence of renewable energy and water desalination and management in arid regions has become increasingly significant. Arid areas, covering more than 20% of Earth's surface, grapple with the dual challenges of elevated energy consumption and hydrological stresses. The imperative shift from a fossil-based economy to a renewable energy-based paradigm offers a transformative potential for electricity production in these regions, leveraging their abundant solar resources (Alawad et al., 2023). Renewable energy sources, encompassing solar thermal and photovoltaic, wind, geothermal, and wave energy, present versatile solutions that can be effectively harnessed across various desalination technologies. These technologies include reverse osmosis, electrodialysis, and mechanical vapor compression (Bermudez, 2022). The synergy between renewable energy sources and desalination methods, coupled with the integration of energy storage systems, holds the promise of meeting water demands in a manner that is both cost-effective and environmentally sustainable (Esmaeilion et al., 2021).

The application of renewable energy in desalination addresses the dual challenge of water scarcity and energy demand in arid regions. Solar energy, in particular, stands out as a renewable resource abundantly available in these areas. Photovoltaic cells and solar thermal collectors can convert sunlight into electricity or heat, providing an energy source for desalination processes. Despite the evident advantages, challenges persist in adopting renewable energy-assisted desalination systems. Notably, the high production costs associated with these systems pose a hurdle, making them less economically competitive when compared to traditional fossil fuel-powered alternatives (Zgalmi et al., 2022). This financial barrier necessitates strategic planning, investment, and ongoing research to enhance the efficiency and affordability of renewable energy technologies in water desalination (Ghazi et al., 2022).

Implementing best practices for integrating renewable energy in water-scarce regions involves a multifaceted approach, focusing on optimizing energy management strategies within microgrids that seamlessly integrate Water Supply Systems (WSSs) (Coimbra, 2022). One key aspect is establishing a sophisticated supply model, evaluating the intricate interdependence between the WSS and islanded sub-systems. This model considers factors such as hydraulic stability and

desalination characteristics to ensure a holistic and efficient integration of renewable energy into the water supply infrastructure (Sui et al., 2021). A two-stage dispatching method proves invaluable to enhance decision-making processes. This approach facilitates day-head decisions, considering real-time power fluctuations and enabling the correction of renewable generation deviations on the fly (Röck, 2017). By incorporating real-time adjustments, this method optimizes renewable energy sources within the dynamic context of water-scarce regions, ensuring a more responsive and reliable energy-water nexus.

Renewable energies, particularly wind and solar power, can play a pivotal role as supplements to the energy-water nexus portfolio. A notable advantage is their independence from water inputs, a critical consideration in water-scarce regions. Their integration diversifies the energy mix and improves the reliability and sustainability of both energy and water supply systems (Ghassemi & Scott, 2021). By mitigating the water dependency of certain energy sources, these renewables offer a strategic avenue to bolster overall system resilience and adaptability. Moreover, acknowledging and addressing uncertainty is paramount in the energy-water nexus planning process. Using fuzzy logic modeling allows for a nuanced consideration of uncertainty factors. This modeling approach captures and processes imprecise or ambiguous information, providing a more robust foundation for decision-making. In the context of the energy-water nexus, where numerous variables and uncertainties come into play, fuzzy logic modeling proves essential for reliable planning and strategic decision-making.

Integrating renewable energy in water-scarce regions demands a comprehensive strategy encompassing optimized energy management, sophisticated supply modeling, real-time decision-making tools, and the thoughtful incorporation of renewable sources that minimize water dependence. By embracing these best practices and accounting for uncertainties through advanced modeling, regions grappling with water scarcity can pave the way for sustainable, resilient, and adaptive energy-water systems.

Harnessing Renewable Energy and Jordan's Water Future

Earning a spot among the world's 10 most water-stressed nations, its inhabitants contend with a meager annual freshwater endowment of less than 100 m^3 per capita—a stark deviation from the global average. This scarcity is exacerbated by a meager annual rainfall of 170 mm, casting a long shadow over the nation's economic, social, and environmental well-being. The burden of water scarcity is particularly pronounced in Jordan's agricultural sector, the backbone of its economy, with over 80% of freshwater consumed by agriculture. Severe resource competition unfolds, putting food security and rural livelihoods at grave risk. Inefficient irrigation practices and water losses only compound the issue, leaving parched fields and empty plates in their wake (UNICEF Jordan, 2023; World Bank, 2023a).

Urban landscapes mirror this struggle, with rapidly growing populations outpacing available resources. Intermittent water shortages and inadequate sanitation facilities become commonplace, especially for vulnerable communities, as domestic demands clash with limited supplies. The climate change specter further looms, casting an ominous shadow over Jordan's water challenges. Erratic rainfall patterns, rising temperatures, and desertification contribute to the depletion of precious water resources, threatening fragile ecosystems. Pollution, a byproduct of unsustainable practices, compounds the crisis, contaminating water supplies, posing health risks, and impeding access to clean water.

Nestled within the arid landscapes of the Middle East (see Figure 1), Jordan confronts the formidable challenge of water scarcity, a relentless adversary intensified by meager rainfall and depleting groundwater resources. During this struggle, a beacon of hope arises from the sun-scorched plains—the prospect of renewable energy. Endowed with abundant sunshine and formidable winds, Jordan possesses a remarkable solar and wind power potential, with estimates indicating an untapped solar PV potential of 18 GW and a wind power potential of 17 GW (Al-Saidi et al., 2015). This latent reservoir offers a transformative pathway toward both energy independence and a proactive approach to addressing the pressing water crisis.

Renewable energy emerges as the linchpin for securing freshwater, decoupling the dependence on erratic rain patterns and dwindling aquifers. Solar and wind power, harnessed adeptly, can fuel desalination plants, converting saline seawater into a vital resource for agricultural fields and homes (Al-Saidi et al., 2016). Studies indicate that substituting fossil fuels with solar energy in desalination processes could potentially halve water production costs (Benson & Clay, 2004), presenting both environmental gains and substantial economic advantages.

The significance of renewable energy transcends the immediate need for water security. It assumes the role of a powerful ally in combating the escalating threat of climate change. The very climate patterns intensifying water scarcity—rising temperatures and altered precipitation—find their roots in the reliance on fossil fuels. The adoption of renewables becomes a proactive measure, reducing greenhouse gas emissions, mitigating the impact of climate change on water resources, and safeguarding Jordan's future resilience (El-Naqa, 2011).

Nevertheless, the transition to a renewable future is not devoid of challenges. The initial costs of infrastructural investments can be substantial, necessitating innovative financing models and international collaboration (IPCC, 2018). Integrating intermittent renewable sources into the existing grid demands robust energy storage solutions to ensure a consistent and reliable power supply (Qadir et al., 2014).

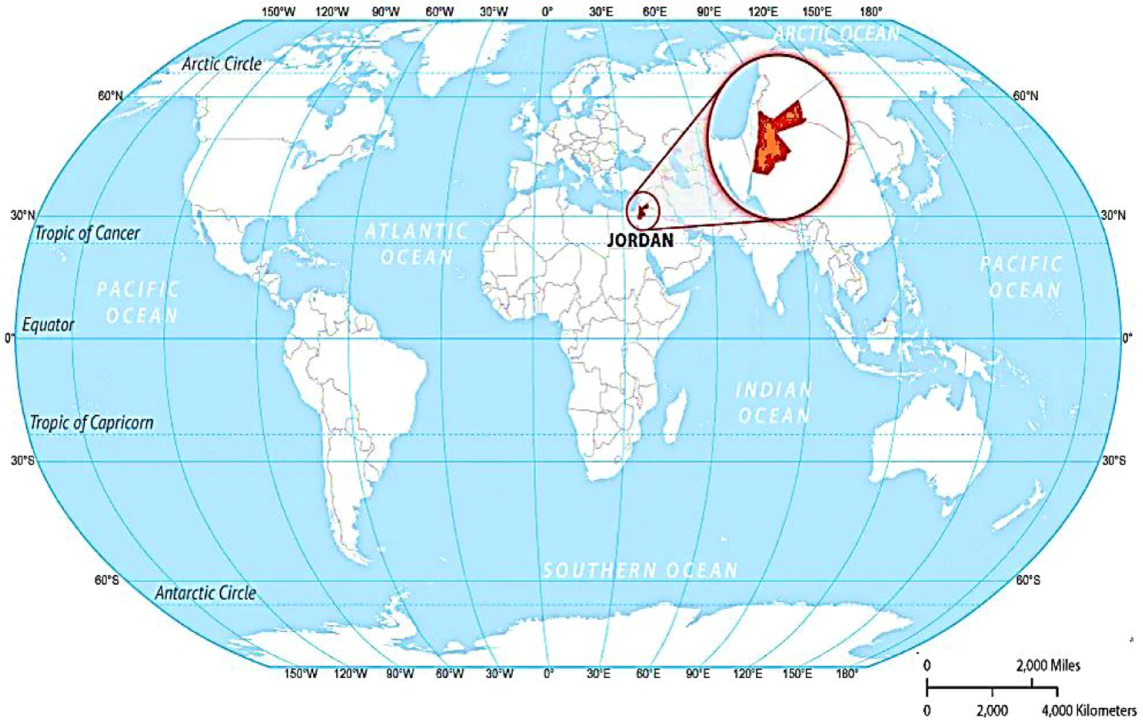

Figure 1. Jordan location map.

Despite these obstacles, Jordan has embarked on this promising journey. Operational PV and wind plants contribute to the national grid, emblematic of the nation's commitment to a greener and more sustainable future (World Bank, 2023b). Furthermore, collaborations with neighboring countries facing similar challenges have the potential to amplify the impact of renewable energy through shared knowledge and joint infrastructure development (World Bank, 2023c). As Jordan strides into a future shaped by renewable energy, the nation stands at the crossroads of innovation, resilience, and a sustainable tomorrow.

Renewable energy presents a golden opportunity for Jordan to rewrite its water narrative. By harnessing its vast renewable potential, Jordan can alleviate water scarcity, mitigate climate change, and propel itself toward a sustainable and prosperous future.

The integration of photovoltaic (PV) systems is emerging as a significant contributor to energy efficiency across various applications, as evidenced by recent research efforts. One study compared the overall energy efficiency of internal combustion engine vehicles with electric vehicles, highlighting the considerable potential of electric vehicles in enhancing energy efficiency. In building performance, another investigation explored renewable energy systems to augment buildings' thermal performance, thereby contributing to enhanced energy efficiency while concurrently reducing construction costs. The research delved into the electricity production potential of installing PV systems on residential building rooftops in Jordan, offering insights into effective strategies for climate change mitigation. Furthermore, using rooftop PV systems as shading devices for uninsulated buildings showcases the multifunctional role of PV technology in enhancing energy efficiency. This exploration extended to semi-arid climate zones, emphasizing the significance of shading with PV panels in bolstering the energy efficiency of buildings. Improving the thermal performance of building envelopes as an approach to enhancing energy efficiency, providing valuable insights for advancing building energy efficiency codes. Collectively, these studies underscore the pivotal role of PV systems in driving energy efficiency across diverse domains, from transportation to building infrastructure (Albatayneh, Albadaineh, Juaidi, Abdallah, Montoya, & Manzano-Agugliaro, 2022; Albatayneh, Albadaineh, Juaidi, Abdallah, Zabalo, & Manzano-Agugliaro, 2022; Albatayneh et al., 2018; Albatayneh, Assaf, Alterman, & Jaradat, 2020; Haj Hussein et al., 2022; Monna et al., 2022).

Several studies have been conducted in the field of energy consumption in Jordan. For instance, on low-income housing retrofits in various climate zones in Jordan, the team assessed the effectiveness of infiltration against roof insulation, providing strategies for improving energy efficiency in retrofitting projects. Another study focused on the thermal assessment of buildings, considering occupants' behavior and the adaptive thermal comfort approach. Their exploration of temperature versus energy-based approaches in building thermal assessment revealed important discrepancies in peak temperature times. Additionally, the researchers evaluated the coupling of photovoltaic (PV) systems with air conditioning versus solar

cooling systems in a case study from Jordan, offering insights into potential synergies between renewable energy and cooling technologies to optimize building energy consumption. These studies enhance our understanding of building performance and energy efficiency, contributing valuable knowledge for developing sustainable and energy-efficient building practices (Albatayneh, Assaf, Jaradat, & Alterman, 2020; Albatayneh et al., 2017a, 2017b, 2017c; 2021).

Jordan is emerging as a leader in the Middle East's renewable energy sector. The nation boasts exceptional potential for harnessing solar and wind power due to its abundant sunshine and strong wind speeds (International Trade Administration, 2024).

This is evident in the significant rise of renewable energy's contribution to the national electricity grid. In 2022, renewables accounted for 27% of electricity generation, a remarkable increase from just 13% in 2019. Reflecting this commitment to sustainability, Jordan has set an ambitious target to achieve 50% of its electricity generation from renewable sources by 2030. Despite these significant strides, Jordan's energy landscape relies heavily on natural gas, which accounted for roughly 68% of electricity generation in 2022. Nonetheless, Jordan's dedication to fostering renewable energy positions it as a frontrunner in the region, paving the way for a more sustainable future (Kharabsheh, 2022).

Jordan is currently pursuing a significant expansion of its water resources by constructing a large-scale desalination plant—the Aqaba-Amman Water Desalination and Conveyance Project (European Investment Bank, 2023). While details regarding the specific energy mix for this project are still emerging, desalination in Jordan has traditionally relied on non-renewable resources like natural gas (Jordan Ministry of Water and Irrigation, 2023). This dependence on fossil fuels raises concerns about long-term sustainability and greenhouse gas emissions. The Aqaba-Amman project, expected to be completed by the end of 2028, offers an opportunity to potentially integrate renewable energy sources into desalination. However, the final energy mix remains to be determined.

Jordan faces a significant challenge with water salinity, particularly in its agricultural sector. Overexploitation of groundwater resources and a lack of natural drainage due to reduced river flows have led to increased salt concentration in the soil (Ministry of Water and Irrigation, 2020). This salinization reduces agricultural productivity and land suitability for certain crops. The Jordan Valley, a historically fertile agricultural region, is particularly affected by this issue (Hammde, 2018). Efforts to address water scarcity, such as desalination projects, can also contribute to salinity concerns, as the brine byproduct can impact water quality if not managed effectively (Alfarra & Mukhopadhyay, 2023).

While Jordan is a leader in adopting renewable energy, challenges remain. Desalination, a potential solution for water scarcity, currently relies on non-renewable energy sources. A large-scale desalination project underway presents an opportunity for integration with renewables, but the final energy mix is undecided. Furthermore, Jordan grapples with water salinity, especially in agriculture, due to overexploited groundwater and reduced river flows. This salinization threatens agricultural productivity. Addressing these interconnected issues—water scarcity, energy use, and salinity—is crucial for Jordan's long-term sustainability.

When powered by renewable energy sources, desalination technologies present another potential avenue for augmenting freshwater supplies, though concerns about environmental impact and energy consumption must be carefully considered. Jordan's water scarcity narrative is reflective of a global challenge. By acknowledging the multifaceted nature of the problem, embracing innovative solutions, and fostering regional cooperation, Jordan can forge a path toward a water-secure future.

The nation confronts a pressing challenge of water scarcity in the arid environs of Jordan, characterized by intense solar exposure and infrequent rainfall. Nevertheless, within this water-stressed context, a prospective synergy emerges—a potential integration of photovoltaic (PV) and wind power plants with advanced desalination technology, all underpinned by a strategic commitment to climate change mitigation. Contemplate expansive arid landscapes with PV panels and wind turbines, dynamically capturing renewable energy. This sustainable energy reservoir serves traditional power needs and invigorates desalination processes, converting saline seawater into potable freshwater. Liberated from the constraints of depleting fossil fuel reserves and unpredictable precipitation, Jordan stands to achieve water sovereignty, ensuring a consistent water supply for agricultural and domestic exigencies.

This collaboration transcends utilitarian objectives, constituting an ecologically conscious endeavor. The substitution of fossil fuels with renewable sources in energy generation and desalination promises a substantial reduction in greenhouse gas emissions—a formidable countermeasure to the climate change dynamics exacerbating water scarcity. Conceptualize Jordan as a region once vulnerable to climatic extremities, now fortified with a water infrastructure resilient to environmental fluctuations. Nevertheless, this intricate choreography encounters stumbling blocks. The initial strides demand a substantial financial investment to establish renewable energy facilities and advanced desalination plants. Efficient and environmentally responsible methodologies for storing solar and wind energy are imperative to ensure a continuous and reliable power supply for desalination processes. As with any intricate dance, precision and forethought must accompany each movement, particularly considering the potential environmental impacts of desalination, such as brine discharge and ecosystem perturbations. Thus, meticulous planning and responsible waste management are critical for sustaining this orchestrated performance.

Despite these challenges, the envisioned rewards beckon as a scientific pursuit. Jordan can redefine its hydrological narrative

by adopting this synthesis of renewable-powered desalination. No longer constrained by water scarcity, it has the potential to emerge as a scientific pioneer—a once arid landscape transformed into an exemplar of technological innovation and ecological resilience. Let the sunlight illuminate the PV panels, the wind energize the turbines, and the desalination plants hum their desalinating tune. Collectively, these elements can engineer a future where Jordan responds harmoniously to the rhythm of water security and leads the scientific discourse—a testament to the transformative potential of renewable energy and an ecologically symbiotic relationship with the environment.

Potential Renewable Energy in Desalination

Several research studies were conducted on the dynamics of the Water-Energy-Food (WEF) nexus, focusing on its relevance in the context of Jordan. Their study on the potential of renewable energy within the WEF nexus explores how renewable sources can contribute significantly to the sustainability of water, energy, and food systems. In a broader regional context, the research team, led by Hindiyeh, expands on the WEF nexus as a comprehensive strategy to address anticipated water scarcity challenges in Arab countries. The interconnectedness of water, energy, and food resources is central to developing holistic solutions. Furthermore, their work extends to preparedness planning for water supply infrastructure, with a notable case study from Irbid, Jordan, addressing potential water terrorism. Additionally, Albatayneh's research emphasizes the role of the Water-Energy-Food Nexus in tackling climate change in the Eastern Mediterranean, providing a comprehensive outlook on addressing environmental challenges. These studies offer valuable insights into the complex relationships within the WEF nexus, presenting a holistic approach to addressing critical issues in water, energy, and food security (Albatayneh, 2023; Albatayneh, Hindiyeh, & AlAmawi, 2022; Hindiyeh et al., 2023, 2021).

In Jordan, the persistent challenge of water scarcity looms ominously. Precipitation is a rarity, akin to the frugality of a miser's tears, and groundwater resources recede akin to the ebbing tide at dusk. However, a prospective solution emerges amidst the arid expanse—renewable energy-powered desalination. This nascent technology presents a promising glimpse into a future where Jordan can simultaneously alleviate its water scarcity, contribute to climate change mitigation, and progress toward sustainable development. The crux of Jordan's water challenges is its reliance on fossil fuels. Traditional desalination methods, tethered to oil and gas, emit greenhouse gases and consume substantial water resources. This symbiotic relationship exacerbates climate change, creating a deleterious cycle of environmental degradation and escalating water insecurity.

Conventional energy sources, primarily fossil fuels, exacerbate the issue. Thermal power plants rely heavily on water for cooling, creating a vicious cycle where scarce water resources are depleted to generate energy, further straining the fragile water system. Additionally, fossil fuel-driven greenhouse gas emissions contribute to climate change, intensifying water scarcity through erratic rainfall patterns and increased desertification.

Recognizing the immense potential of renewables, Jordan has embarked on an ambitious clean energy transition. The government has set ambitious targets to generate 80% of electricity from renewables by 2030. Several large-scale solar and wind power plants have been established, and policies incentivizing rooftop solar installations encourage public participation.

However, challenges remain. Initial costs of renewable infrastructure deployment can be high, requiring continued government support and private investment. Grid integration and storage solutions need further development to handle the intermittent nature of solar and wind power. Capacity building and public awareness campaigns are crucial to ensure community buy-in and maximize the benefits of renewables.

A transformative wind of change is stirring. Leveraging the abundant solar and wind resources in Jordan, renewable energy emerges as a clean alternative. Solar and wind power offer an emissions-free energy bounty comparable to tireless nomads traversing the desert. By integrating these renewable sources into desalination processes, Jordan can liberate itself from fossil fuel dependency, charting a new trajectory for its water narrative. This paradigm shift promises a plethora of advantages. Picture desalination plants humming with the sun's power, emancipated from the caprices of rain patterns and depleting aquifers. The resulting freshwater, extracted from the saline grasp of the ocean, holds the potential to nourish arid fields and homes, fostering food security and an elevated standard of living for the populace.

Nevertheless, the benefits extend beyond satiating immediate thirst. Severing ties with fossil fuels would strike a decisive blow against climate change, precipitating a substantial reduction in greenhouse gas emissions. This action, in turn, would mitigate the impact of escalating temperatures, fortifying vital water resources. Simultaneously, energy security would be enhanced as Jordan forges its water future from the abundant sun and wind resources, reducing dependence on volatile energy imports. However, this sunlit path is not bereft of challenges. Initial investment costs for renewable energy infrastructure and desalination plants loom large, necessitating innovative financing models and international collaboration. The sun and wind, though generous benefactors, exhibit occasional fickleness, demanding robust energy storage solutions to ensure a consistent water supply. Even the extraction of life from the sea casts shadows, with concerns about brine discharge and potential ecosystem disruption.

Embracing technological advancements, including efficient storage solutions and responsible waste management, offers avenues to minimize the environmental impact of desalination. While intricate, integrating renewable energy sources into existing grids is attainable with meticulous planning and strategic infrastructure upgrades. Moreover, social and political concerns can be addressed by engaging communities and

ensuring equitable distribution of benefits, ultimately transforming the desert into a landscape of shared prosperity.

In the arid landscapes of Jordan, where water scarcity poses a persistent challenge, the demand for water desalination remains a critical imperative. This process, albeit indispensable, entails substantial energy consumption, underscoring the crucial need for a sustainable and economically viable energy source. In this context, renewable energy emerges as the linchpin for meeting Jordan's formidable energy demands of water desalination. Recent data underscores the criticality of renewable energy in addressing Jordan's water challenges. Providing renewable energy at optimal costs aligns with the nation's goal of efficiently securing its water needs and transporting it to population centers. The nexus between renewable energy and water desalination becomes increasingly pertinent as Jordan grapples with the dual challenges of water scarcity and the energy-intensive nature of desalination processes.

Providing renewable energy at competitive prices is paramount for Jordan's water management strategy. Recent advancements and investments in renewable energy infrastructure, such as solar and wind power, highlight the nation's commitment to harnessing environmentally sustainable sources. The efficacy of integrating these renewable sources into the energy portfolio is crucial not only for mitigating the environmental impact but also for optimizing the cost-effectiveness of water desalination. Moreover, aligning renewable energy with water desalination serves as a multifaceted solution. It not only addresses immediate water needs but also holds the potential to significantly impact agricultural practices in Jordan. By increasing water availability through efficient desalination processes, the agricultural sector can expand, bolstering food security and contributing to the nation's overall resilience in the face of water scarcity.

Recent data underscores the urgency of adopting renewable energy to meet Jordan's water demands efficiently. Integrating renewable energy into water desalination offers a sustainable solution to the energy-intensive nature of the process but also aligns with broader national objectives, including cost-effectiveness, increased agricultural output, and enhanced food security. As Jordan navigates its water-energy nexus, the strategic deployment of renewable energy emerges as a pivotal driver for shaping a more resilient and sustainable future.

Renewable energy-powered desalination is not just a technological option for Jordan but a lifeline. It offers a chance to break free from the shackles of water scarcity, combat climate change, and build a sustainable future. Jordan can transform its sunlit path toward water security and sustainable development by overcoming challenges through innovation, collaboration, and responsible stewardship. Harnessing this clean energy to power desalination plants offers transformative benefits:

- *Water Independence*: Unchained from fossil fuels, Jordan can reclaim control over its water future. With renewable energy providing the muscle, desalination facilities can churn out life-giving freshwater independent of fickle rain patterns and dwindling aquifers. This ensures stable water supplies for homes, cities, and industries, paving the way for economic and social development.
- *Climate Change Mitigation*: By severing ties with fossil fuels, Jordan would deal a powerful blow to climate change. Greenhouse gas emissions would plummet, reducing the impact of warming temperatures and safeguarding vital water resources. This benefits Jordan and contributes to a global fight against climate change.
- *Energy Security*: Embracing renewable energy empowers Jordan to craft its energy future, mitigating dependence on volatile energy imports. This bolsters national security and creates potential cost savings, translating into lower water production costs and increased affordability for citizens.
- *Food Security*: With secure water supplies, Jordan can expand its agricultural footprint, transforming arid lands into verdant fields. This enhances food security, reduces reliance on imports, and creates new economic opportunities for rural communities.

Case Study—Jordan National Carrier

For Jordan, access to fresh water is a constant struggle. Rain falls like a miser's tears, and groundwater dwindles like a retreating tide. However, on the horizon gleams a ray of hope: the ambitious National Water Carrier Project, a 450-kilometer pipeline poised to transport desalinated water from the Red Sea to quench the thirst of millions. This monumental undertaking is a testament to Jordan's ingenuity and a crucial step toward water security and sustainable development.

The importance of the National Carrier cannot be overstated. Today, Jordan faces a dire water crisis, with per capita water availability at 84% below the global average (World Bank, 2023b). Traditional sources like groundwater and rain are rapidly depleting, forcing reliance on expensive and environmentally detrimental water imports. The National Carrier offers a transformative solution. Generating up to 300 million m^3 of desalinated water annually can meet one-third of Jordan's estimated water demands (Ministry of Water and Irrigation, 2022). This would ensure a reliable water supply for homes and cities and empower farmers to cultivate previously arid lands, boosting food security and economic growth (Haddadin, 2023). But the National Carrier's true brilliance lies in its commitment to renewable energy. The project plans to leverage Jordan's abundant sunshine and wind power to fuel the desalination process, recognizing the urgent need to combat climate change and reduce dependence on fossil fuels. This avoids greenhouse gas emissions and air pollution and promises significant cost savings in the long run. By reducing reliance on imported energy, the National Carrier can provide affordable water for all, promoting social and economic equity (International Finance Corporation, 2023).

Table 1. Desalination Cost Summary for Jordan ($/m^3).

FUEL SOURCE	TECHNOLOGY	ESTIMATED COST RANGE ($/M^3)	POTENTIAL RECENT TRENDS
Fossil fuels	RO (Natural Gas)	0.75–1.40	Slight increase with global gas price fluctuations
	MED/MSF (Oil)	1.30–2.30	Potential decrease due to recent oil price drops
Renewables	RO (Solar PV)	0.95–2.00	Solar panel cost decreases may lower future costs
	RO (Wind)	0.85–1.70	Wind resource utilization improvements might lower costs
Hybrid systems	RO (Solar and Wind)	0.70–1.55	Advancements in storage solutions may offer further cost optimization

Source. Jordanian Ministry of Planning and International Cooperation (2023), World Bank (2023d), International Gas Report (2023), Batarseh (2018), World Bank Data (2022a, 2022b, 2022c), and Ghalavand et al. (2023).
Note. (1) The costs are estimations based on current data and assumptions. Actual costs may vary. (2) Initial capital costs for renewable-based plants can be higher, impacting long-term costs. (3) Government policies and incentives can influence feasibility.

The National Carrier is not just a pipeline but a vital artery pumping life-giving water into a thirsty land. By embracing sustainable technology and harnessing the power of renewable energy, it offers a roadmap toward a brighter future for Jordan. With abundant water flowing through its veins, Jordan can transform its parched landscapes into verdant fields, nourish its people, and build a resilient economy. The National Carrier stands as a beacon of hope not only for Jordan but also for the world, demonstrating that even in the face of daunting challenges, ingenuity and unwavering commitment can pave the way for a sustainable future where water, the elixir of life, flows freely for all.

Calculating the precise cost of desalinated water in Jordan requires considering various factors influencing the final price. However, some estimations and insights are based on Jordanian specificities and recent data (see Table 1). These are estimated ranges based on current data and assumptions. Actual costs vary significantly depending on specific project details, technology choices, financing arrangements, and operational efficiency. Initial capital costs for renewable energy-based desalination plants can be higher than fossil fuel options, impacting the levelized cost of water over the plant's lifetime. Government policies and incentives promoting renewable energy can significantly influence the economic feasibility of renewable desalination projects in Jordan.

While fossil fuels currently lead in terms of lower baseline cost, their environmental impact and price volatility raise concerns. Despite potentially higher initial costs, Renewables offer long-term cost reduction potential and environmental sustainability advantages. The optimal fuel choice for Jordan's desalination projects will depend on carefully analyzing specific project contexts considering economic, environmental, and policy factors.

Conclusion

Renewable energy presents a golden opportunity for Jordan to rewrite its water narrative. By harnessing its vast renewable potential, Jordan can alleviate water scarcity, mitigate climate change, and propel itself toward a sustainable and prosperous future. Overcoming the challenges through innovative solutions, international partnerships, and responsible environmental practices will illuminate the path to a future.

Jordan is a microcosm of the global water crisis and the critical role of renewable energy in navigating it. Using its abundant solar and wind resources, Jordan can alleviate water scarcity, mitigate climate change, and pave the way for a sustainable future. The journey is not without its obstacles, but continued commitment from all stakeholders, including government, private sector, and communities, can transform Jordan into a regional leader in water-wise renewable energy development, providing valuable lessons for other water-scarce nations.

By dedicating resources to further research and development, Jordan can solidify its position as a pioneer in water-scarce renewable energy implementation, offering a model for other vulnerable nations struggling with similar challenges.

In conclusion, integrating renewable energy in water-scarce regions demands a comprehensive strategy encompassing optimized energy management, sophisticated supply modeling, real-time decision-making tools, and the thoughtful incorporation of renewable sources that minimize water dependence. By embracing these best practices and accounting for uncertainties through advanced modeling, regions grappling with water scarcity can pave the way for sustainable, resilient, and adaptive energy-water systems.

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