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TOWARD LOW-CARBON WATER TREATMENT IN KAZAKHSTAN: RENEWABLE ENERGY OPPORTUNITIES AND BARRIERS

Ramazan A.*, Taizhanova L.
Yessenov University, Aktau, Kazakhstan
e-mail: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz

Abstract. Kazakhstan's water sector combines high regional scarcity, aging infrastructure, dependence on transboundary flows, and a carbon-intensive electricity supply. This review evaluates whether renewable energy can support lower-carbon water treatment and desalination under these constraints. A narrative synthesis of 13 sources published from 2018 to 2025 examined Kazakhstan and comparable treatment settings. Evidence was synthesized across three dimensions: the suitability of treatment processes for variable power, the spatial match between renewable resources and water demand, and implementation barriers. Reverse osmosis, membrane bioreactors, ultraviolet oxidation, and conventional biological treatment were compared qualitatively by energy demand, tolerance to intermittent operation, maturity, and principal environmental risk. The evidence indicates that solar photovoltaic systems are promising for modular treatment in southern and western regions, whereas wind power has potential for larger coastal desalination facilities in Mangystau. Hybrid systems with storage or grid backup are preferable to stand-alone renewable supply for processes requiring continuous pressure or aeration. The main constraints are not resource availability alone but high initial cost, weak grid flexibility, aging water networks, limited operational data, fragmented governance, and brine management. Renewable integration can reduce operational emissions, but the magnitude cannot be generalized without facility-specific electricity, recovery, chemical, and brine-disposal data. A phased pathway is proposed: reduce network losses first, conduct energy and water audits, pilot hybrid systems, and apply life-cycle assessment before scale-up. The review concludes that renewable-powered treatment is technically plausible in Kazakhstan, but credible decarbonization requires monitored demonstrations and coordinated water-energy planning.

Keywords: water treatment, renewable energy, desalination, reverse osmosis, decarbonization, Kazakhstan, water security.

Introduction

Water security in Kazakhstan is shaped by pronounced spatial variability, a dry continental climate, aging treatment and conveyance assets, and dependence on rivers shared with neighboring states. These conditions create a coupled problem: more treatment and desalination may be needed precisely where electricity supply is carbon intensive or infrastructure is least reliable. Water-sector modernization therefore cannot be assessed separately from the energy transition. The institutional dimension is equally important because fragmented responsibilities can delay investment and obscure accountability for water quality and physical losses [3].

Kazakhstan has strong wind resources across the steppe and substantial solar resources in southern and western regions. Yet the presence of a renewable resource does not by itself establish the feasibility of a water-treatment project. Treatment technologies differ in their need for continuous power, pressure stability, pretreatment, skilled operation, chemical supply, and residuals management. Reverse osmosis can be coupled with photovoltaic or wind generation, but intermittent supply may increase cycling, membrane stress, and production variability unless storage, a grid connection, or a hybrid configuration is provided [8]. Biological processes also require reliable aeration and control, while ultraviolet and advanced oxidation systems are sensitive to water quality and energy dose.

Previous work has discussed Kazakhstan's water pollution, renewable-energy potential, and individual treatment technologies, but these topics are often treated independently. Central Asian evidence confirms continuing pressure from municipal, agricultural, and industrial pollution [6], while research on Kazakhstan's wind development shows that resource potential is mediated by grid, investment, and policy constraints [5]. A useful assessment must therefore connect treatment performance, energy-system characteristics, environmental burdens, and governance.

The purpose of this review is to evaluate the practical role of renewable energy in Kazakhstan's water treatment and desalination sector. The objectives are to identify technology–energy combinations suited to different regional conditions; compare their operational and environmental trade-offs; determine the main barriers to implementation; and propose a phased pathway for pilot projects and subsequent scale-up. The review does not estimate a national emissions-reduction total because the available studies use heterogeneous boundaries and rarely disclose complete plant-level inventories.

Materials and methods

This article presents a narrative review and qualitative synthesis of the literature already assembled for the manuscript. The retained corpus comprises 13 cited sources published between 2018 and 2025: journal articles on water treatment, renewable energy, and regional environmental constraints, together with an official environmental code. The scope is Kazakhstan, with evidence from comparable treatment applications used to identify engineering implications. No new database search or statistical meta-analysis was performed for this revision. Because a dated search log, database export, and screening counts were unavailable, the review is not presented as systematic or exhaustive.

The retained sources were organized by treatment purpose, operational energy requirements, regional context, residuals management, and implementation constraints. Technology-specific evidence was distinguished from the authors' interpretation for Kazakhstan. The synthesis does not pool energy or emissions values because the sources differ in feedwater quality, treatment scale, product-water requirements, and system boundaries. The technology and implementation tables therefore provide qualitative comparisons and recommendations rather than measured rankings of Kazakhstan facilities.

For the qualitative comparison, renewable compatibility describes the flexibility of the complete treatment system, including buffering and backup. High compatibility means that scheduled operation or water storage can accommodate variable supply; medium compatibility means that controlled ramping, storage, or grid support is generally necessary. These categories are engineering judgments used in this review, not standardized scores or experimentally validated performance levels. Energy profiles are relative descriptions rather than specific energy consumption measurements.

The interpretation followed a decision sequence: characterize the water source and product-water requirement; establish a measured water and energy baseline; reduce avoidable losses; select an appropriate treatment process; and evaluate renewable generation, storage, and backup. Life-cycle assessment is proposed as a subsequent project-level validation step. No original life-cycle inventory, emissions calculation, or optimization model is reported in this article.

Results

The evidence supports a differentiated rather than uniform transition. Conventional mechanical and biological processes remain necessary for municipal treatment and pretreatment, whereas membrane systems are relevant for saline groundwater, industrial reuse, and Caspian seawater desalination. Innovative technologies can reduce loading on urban wastewater plants, but their effectiveness depends on influent characteristics and operational control [2]. A submerged membrane bioreactor can provide high effluent quality and a smaller footprint than conventional biological treatment, although energy demand and membrane fouling remain important constraints [4]. Table 1 summarizes the qualitative technology comparison; its ratings represent the synthesis described in Materials and methods.

Table 1 – Comparative suitability of treatment technologies for renewable integration

Technology	Primary use	Energy profile	Renewable compatibility	Main limitation
Mechanical treatment	Solids removal and pretreatment	Low to medium; pumping dominates	High when flow can be buffered	Does not remove dissolved contaminants
Activated sludge	Municipal wastewater	Continuous aeration demand	Medium with grid or storage support	Process instability if aeration is interrupted
Membrane bioreactor	High-quality wastewater reuse	Medium to high and continuous	Medium	Fouling, aeration energy, skilled operation
Reverse osmosis	Desalination and dissolved-solids removal	High-pressure pumping	Medium; hybrid supply preferred	Concentrate disposal and membrane fouling
Ultraviolet/advanced oxidation	Disinfection and micropollutant control	Dose depends on water quality	Medium to high with buffering	Pretreatment and electricity demand
Waste stabilization ponds	Low-cost rural wastewater treatment	Low direct electricity demand	High	Large land area and seasonal performance

Reverse osmosis is the principal candidate for low-carbon desalination because it uses electricity rather than the large thermal input required by thermal desalination. Renewable-powered systems have been demonstrated in arid settings, but performance depends on feed salinity, recovery, pressure, pretreatment, and the chosen buffering strategy [8]. Groundwater desalination and decontamination experiments in Aktau also demonstrate the local relevance of feedwater-specific testing [12]. In western Kazakhstan, wind and solar generation could reduce exposure to fossil-based grid electricity, while modular photovoltaic systems may serve small remote settlements. For a large coastal plant, however, continuous production obligations make a hybrid configuration more credible than an isolated renewable system.

Residuals management is a decisive environmental issue. A lower-carbon electricity supply does not eliminate the ecological risk from concentrated brine, antiscalants, cleaning chemicals, or rejected contaminants. Recovery of salts and metals from reverse-osmosis concentrate is technically promising, but commercial viability remains site-specific [9]. Projects should therefore compare discharge, dilution, evaporation, resource recovery, and zero-liquid-discharge options using local hydrodynamic and ecological data rather than treating brine as a secondary issue.

The regional match between energy resources and water needs is favorable but uneven. Southern Kazakhstan has a strong case for solar-powered decentralized treatment, irrigation-water polishing, and potable systems where daytime operation and storage of treated water can buffer electricity variability. Mangystau has both acute water demand and access to strong wind and solar resources, making it a candidate region for hybrid renewable desalination. Northern and eastern regions may benefit more from energy-efficiency retrofits, wastewater reuse, and locally appropriate wind or small-hydropower combinations. Spatial planning tools can support siting decisions, but they must integrate water quality, grid access, land, ecological sensitivity, and demand rather than renewable potential alone [7].

The synthesis suggests three recurring design requirements: a match between treatment purpose and source-water quality, a reliable power and water buffer, and explicit management of

brine or sludge. Figure 1 summarizes how these requirements can be incorporated into project selection. The diagram is a conceptual outcome of this review; it does not represent a simulated or commissioned facility.

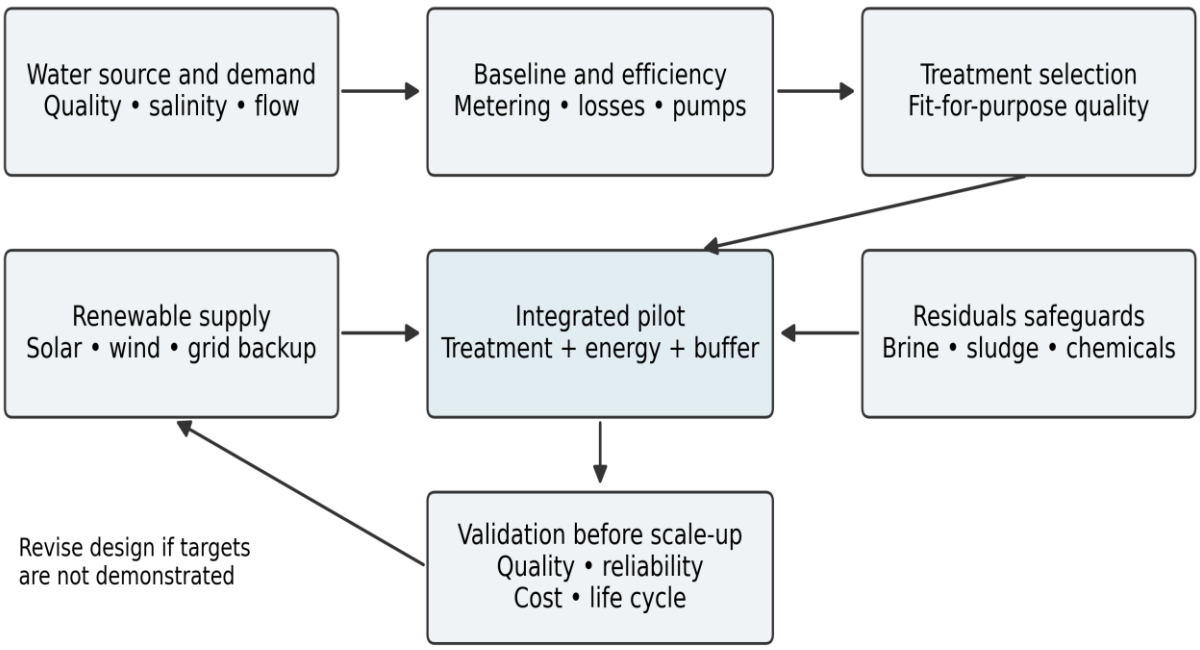


Figure 1 – Conceptual framework for renewable-powered water treatment in Kazakhstan

Source: authors' qualitative synthesis. Arrows indicate the proposed decision sequence and design feedback.

Discussion

The energy transition also faces system-level constraints. Wind development in Kazakhstan has historically been limited by transmission, investment risk, and institutional capacity despite strong physical potential [5]. Solar photovoltaic expansion requires grid standards, forecasting, and storage or demand management to maintain reliability [10]. These constraints are particularly important for treatment processes that cannot tolerate extended shutdowns. Treated-water reservoirs, variable-frequency drives, pressure vessels, and flexible scheduling can provide part of the required buffer and may be less costly than batteries for every application.

Water-system efficiency must precede or accompany new generation. Where conveyance and distribution losses are high, adding renewable electricity can decarbonize pumping but still wastes water and installed capacity. The preferred order is leakage control, metering, pump optimization, process control, and only then renewable sizing. This order also improves the quality of the baseline needed for life-cycle and cost assessment. Kazakhstan's Environmental Code provides a formal basis for pollution prevention and environmental assessment, but project-level monitoring is needed to translate regulatory objectives into comparable evidence [11]. Table 2 translates these considerations into context-specific implementation recommendations.

Table 2 – Recommended implementation pathway by context

Context	Preferred configuration	Required evidence before investment	Priority safeguard
Remote southern settlement	Solar photovoltaic treatment with treated-water storage and backup	Hourly demand, feedwater quality, seasonal irradiance, operator capacity	Safe residuals handling and reliable disinfection
Mangystau coastal desalination	Wind–solar–grid hybrid reverse osmosis with energy recovery	Salinity, intake ecology, load profile, grid constraints, brine dispersion	Marine impact assessment and concentrate monitoring
Urban wastewater plant	Efficiency retrofit plus solar or wind power purchase; consider membrane upgrade only for reuse	Aeration and pumping sub-metering, effluent target, sludge route	Avoid higher life-cycle burden from unnecessary treatment
Agricultural reuse scheme	Fit-for-purpose treatment linked to irrigation demand	Crop standard, seasonal storage, salinity and nutrient balance	Soil salinization and health-risk control
Industrial facility	Process integration, reuse, and hybrid electricity	Contaminant-specific mass balance and production schedule	Prevent transfer of pollution to concentrate or sludge

A credible pilot program should report a minimum dataset: feed and product water quality; hourly electricity consumption; specific energy consumption per cubic metre; water recovery; chemical consumption; membrane and filter replacement; downtime; renewable fraction; storage losses; concentrate or sludge quantity and quality; and capital and operating expenditure. Without these variables, reported percentages of emissions or cost reduction are not transferable. The same functional unit and quality target must be used when comparing alternatives.

Life-cycle assessment is necessary because operational electricity is only one source of impact. A low-grid-emission scenario can shift the relative importance toward membranes, chemicals, construction materials, storage, and end-of-life treatment. Conversely, in a coal-dominated grid, renewable electricity may dominate the improvement. The assessment should follow a cradle-to-grave boundary where data permit, test grid and renewable scenarios, and report sensitivity to membrane life, recovery, storage replacement, and brine management. Claims of carbon reduction should be expressed as scenario results with uncertainty, not as a single national value.

Governance remains a cross-cutting barrier. Water and energy planning use different datasets, investment cycles, and performance indicators. A joint program should therefore select pilots using shared criteria and publish harmonized monitoring results. Basin-level water constraints must also be respected: climate-driven runoff change in the Tianshan region and long-term uncertainty for the Lake Balkhash basin show that supply projections cannot rely on historical averages alone [1, 13]. Renewable-powered treatment improves the quality or accessibility of water but does not create unlimited freshwater.

The most defensible near-term strategy is incremental. In the first stage, utilities should audit losses, energy use, and water quality. In the second stage, small hybrid pilots should be deployed in locations with a clear treatment need and measurable baseline. In the third stage, life-cycle, reliability, and cost results should be independently compared with conventional alternatives. Only configurations that meet water-quality targets and demonstrate environmental improvement under local conditions should proceed to wider replication.

Conclusions

Renewable energy can support the decarbonization and extension of water treatment in Kazakhstan, but the appropriate configuration depends on regional water quality, demand, grid conditions, and operational capacity. Solar photovoltaic systems are well suited to modular and schedulable treatment in southern and remote areas, while wind–solar hybrid supply has stronger potential for large desalination projects in Mangystau. Processes requiring stable pressure or continuous aeration should not be designed around variable generation without treated-water storage, electrical storage, grid support, or another reliable backup. The review also shows that renewable supply alone is insufficient: network losses, inefficient pumping, membrane fouling, brine disposal, fragmented governance, and limited monitoring can negate the expected benefit. Kazakhstan should therefore prioritize water and energy audits, leakage reduction, fit-for-purpose treatment, and monitored hybrid pilots before large-scale replication. Each pilot should report comparable water-quality, energy, recovery, chemical, residuals, reliability, cost, and life-cycle indicators. Under this evidence-based pathway, renewable-powered treatment can contribute to water security and lower operational emissions without overstating benefits or transferring impacts to brine, sludge, materials, or storage systems.

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ҚАЗАҚСТАНДАҒЫ ТӨМЕН КӨМІРТЕКТІ СУ ТАЗАРТУҒА КӨШУ: ЖАҢАРТЫЛАТЫН ЭНЕРГЕТИКАНЫҢ МҮМКІНДІКТЕРІ МЕН КЕДЕРГІЛЕРІ

А. Рамазан, Л. Тайжанова
Есенов университеті, Ақтау қ., Қазақстан.
e-mail: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz

Аңдатпа. Қазақстанның су секторына өңірлік су тапшылығы, ескірген инфрақұрылым, трансшекаралық ағындарға тәуелділік және көміртек сыйымдылығы жоғары электрмен жабдықтау қатар әсер етеді. Бұл шолуда жаңартылатын энергия көздерін су тазарту және тұщыландыру жүйелеріне енгізудің техникалық және экологиялық орындылығы бағаланды. Қазақстан және ұқсас қуаң өңірлер бойынша ағылшын тіліндегі рецензияланған еңбектер мен ресми құжаттар талданып, тазарту үдерістерінің айнымалы қуатқа бейімділігі, жаңартылатын ресурстардың су сұранысымен аумақтық сәйкестігі және енгізу кедергілері қарастырылды. Кері осмос, мембраналық биореакторлар, ультракүлгін тотығу және дәстүрлі биологиялық тазарту энергия қажеттілігі, технологиялық жетілуі және негізгі экологиялық тәуекелдері бойынша салыстырылды. Нәтижелер оңтүстік және батыс өңірлердегі модульдік жүйелер үшін күн энергетикасының, ал Маңғыстаудағы ірі тұщыландыру нысандары үшін жел энергетикасының әлеуеті жоғары екенін көрсетті. Үздіксіз қысым немесе аэрация талап етілетін үдерістерде энергия сақтау жүйесі не электр желісінің резерві бар гибридтік шешімдер қажет. Негізгі шектеулерге бастапқы капиталдық шығын, желінің әлсіз икемділігі, су құбырларының тозуы, пайдалану деректерінің тапшылығы, басқарудың бөлшектенуі және тұзды концентратты басқару жатады. Жүйелерді кеңейтудің алдында су мен энергия аудитін өткізу, шығындарды азайту, гибридтік пилоттарды сынау және өмірлік циклді бағалау ұсынылады.

Түйін сөздер: су тазарту, жаңартылатын энергия, тұщыландыру, кері осмос, көміртексіздендіру, Қазақстан, су қауіпсіздігі.

НА ПУТИ К НИЗКОУГЛЕРОДНОЙ ВОДООЧИСТКЕ В КАЗАХСТАНЕ: ВОЗМОЖНОСТИ И БАРЬЕРЫ ВОЗОБНОВЛЯЕМОЙ ЭНЕРГЕТИКИ

Рамазан А., Тайжанова Л.
Университет Есенова, г. Актау, Казахстан.
e-mail: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz

Аннотация. Водный сектор Казахстана одновременно испытывает региональный дефицит воды, износ инфраструктуры, зависимость от трансграничного стока и воздействие

углеродоёмкого электроснабжения. В обзоре оценена техническая и экологическая обоснованность применения возобновляемой энергии для водоочистки и опреснения. Проанализированы англоязычные рецензируемые публикации и официальные документы по Казахстану и сопоставимым засушливым регионам. Синтез охватывал совместимость процессов очистки с переменной генерацией, территориальное соответствие энергетических ресурсов спросу на воду и ограничения внедрения. Обратный осмос, мембранные биореакторы, ультрафиолетовое окисление и традиционная биологическая очистка сопоставлены по энергопотреблению, технологической зрелости и основным экологическим рискам. Результаты указывают, что солнечная энергетика наиболее пригодна для модульных систем в южных и западных регионах, а ветровая энергетика имеет больший потенциал для крупных опреснительных объектов Мангистау. Для процессов, требующих постоянного давления или аэрации, предпочтительны гибридные системы с накоплением энергии либо резервом сети. Ключевыми ограничениями остаются высокие первоначальные затраты, недостаточная гибкость энергосистемы, изношенные водопроводные сети, дефицит эксплуатационных данных, фрагментированное управление и обращение с рассолом. До масштабирования рекомендуется сократить потери воды, провести энергетический и водный аудит, испытать гибридные пилотные установки и выполнить оценку жизненного цикла. Возобновляемая водоочистка технически осуществима, но подтверждение декарбонизации требует измеряемых демонстрационных проектов и согласованного планирования водного и энергетического секторов.

Ключевые слова: водоочистка, возобновляемая энергия, опреснение, обратный осмос, декарбонизация, Казахстан, водная безопасность.