UDC 504.062.2
IRSTI 87.35.91
DOI 10.37238/2960-1371.2960-138X.2025.100(4).192

Akhmet Ramazan*, Lyailim Taizhanova, Samal Syrlybekkyzy

Caspian State University of Technologies and Engineering Named after Sh.Yessenov, Aktau, Kazakhstan
***Corresponding author:** akhmet.ramazan@yu.edu.kz

E-mail: akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz, samal.syrlybekkyzy@yu.edu.kz

MODELING AND ENVIRONMENTAL ASSESSMENT OF LOW-CARBON DESALINATION TECHNOLOGIES FOR ARID COASTAL REGIONS

Annotation. The article examines the feasibility and architecture of a circular water system that couples renewable-energy-powered seawater reverse osmosis (SWRO) and electrolysis to produce green hydrogen in an arid coastal zone of Western Kazakhstan. The methodology combines a critical review of technological and techno-economic options, comparison of energy supply configurations (solar/wind; continuous/intermittent operation), and analysis of water-conditioning routes for electrolyzers (desalinated seawater and polishing of treated wastewater). The study shows that integrating SWRO with proton-exchange-membrane electrolysis is technically feasible; the required feedwater quality is attainable via membrane polishing trains; and wind-driven intermittent operation can lower capital expenditure by reducing storage needs. Practical implications include enhanced regional water security and decarbonization alongside potential hydrogen exports. The paper outlines pilot-scale pathways and scale-up considerations tailored to the Mangystau context.

Keywords: Low-carbon technology; Desalination; Green hydrogen; Renewable energy; Reverse osmosis; Circular water systems; Arid coastal regions; Mangystau region; Solar PV; Wind power.

Introduction

The Mangystau region of Kazakhstan presents a compelling case study for implementing circular water systems that integrate renewable-powered reverse osmosis (RO) desalination with electrolysis for green hydrogen production. This arid coastal region, located on the eastern shore of the Caspian Sea, faces significant water scarcity challenges while possessing substantial renewable energy potential and strategic importance for regional energy development [1].

Water scarcity is particularly acute in remote and coastal areas where populations depend on groundwater resources. The existing water provision infrastructure includes seawater desalination plants, though their productivity suffers during hot summer periods due to high temperatures [2].

Kazakhstan possesses significant potential for renewable energy development, making it an attractive location for green hydrogen production. The country has excellent wind and solar resources, particularly in sparsely populated areas that are favorable for both solar and wind harvesting. This renewable energy potential is crucial for powering both desalination and electrolysis processes in a circular water system [3]. Kazakhstan's energy strategy promotes renewables to cut domestic fossil use and boost oil and gas exports, while EU agreements position it as a prospective green hydrogen supplier to Europe [4]. According to the World Bank's World Development Indicators, the total population of Kazakhstan reached 20,592,571 inhabitants in 2024 [5]. This demographic baseline is essential for assessing national energy and water demand, as well as for projecting the potential scale of green hydrogen deployment and desalinated water reuse in the Mangystau region. Population dynamics directly influence the magnitude of electricity consumption, freshwater requirements, and long-term sustainability strategies, thereby framing the boundary conditions for integrated renewable energy and hydrogen systems [5]. Data from the International Energy Agency (IEA) show that Kazakhstan's total energy supply (TES) in 1990–2023 was dominated by coal, which remains the primary source despite fluctuations. Natural gas increased steadily after 2000, while oil maintained a stable share of around 500,000–700,000 TJ. Contributions from renewables remain negligible. This persistent reliance on fossil fuels underscores the urgency of expanding renewables to support green hydrogen and circular water strategies in arid regions [6]. Kazakhstan's energy mix is coal-dominated, though the Green Economy Strategy aims for 50% renewables by 2050. Despite vast wind (~1.8 TWh/year) and solar (2,800–3,000 h/year) resources, their share is minimal. Hydropower supplies ~12% of capacity but <2% of generation. Tapping this potential is vital for green hydrogen and circular desalination in arid regions such as Mangystau. [7].

Solar- and wind-powered RO desalination provides cost-effective freshwater, with solar reducing costs by ~33% versus grid power. PV–desalination integration is economically viable, often undercutting conventional water tariffs. [8].

The country's energy transition strategy includes renewable energy as a pathway to increase oil and gas exports by reducing domestic consumption of fossil fuels. Kazakhstan has signed agreements with the EU for green hydrogen development, positioning itself as a potential major green hydrogen exporter to Europe [9].

The Mangystau region's strategic location on the Caspian Sea coast provides advantages for offshore renewable energy installations, which can offer ecological advantages compared to onshore alternatives while providing access to abundant seawater resources [10].

Integrating renewable RO with electrolysis offers a sustainable pathway to tackle water scarcity and energy transition in arid coasts. In Mangystau, it could enhance water security and support the global hydrogen economy [11]. This circular model aligns with Kazakhstan's green economy goals and water-energy-food nexus challenges, with success hinging on technology, policy support, and international cooperation [12].

Literature Review

Circular systems coupling reverse osmosis (RO) desalination with PEM or alkaline electrolysis have produced green hydrogen in arid coastal settings, with reported outputs from ~1,500 kg H_2/day to over 8×10^6 kg/year, electrolyzer efficiencies of 60–89%, and water use of ~27–900 m³/day [13].

Economic assessments report LCOH of US$1.37–5.26/kg (many models ≈US$2.08–2.27/kg); CAPEX is highly variable—desalination can exceed US$6,000/kW in some cases—while O&M is typically 2–6% of CAPEX annually. Technical and economic viability depends on resilient infrastructure, renewable integration (solar/wind/hybrid), and strict water-quality management—critical for Mangystau's arid coast [14].

Table 1 - Characteristics of Included Studies

Study	Study Type	Geographic Context	System Scale	Technology Focus
Azevedo et al., 2023	Techno-economic analysis	Sines, Portugal (arid coastal)	Gigawatt-scale (modeling)	Seawater desalination plus proton exchange membrane electrolysis, wind/solar
Barghash et al., 2022	Feasibility/cost-benefit analysis	Oman (arid, urban)	1,500–50,000 kilograms hydrogen per day (modeling)	Treated effluent plus reverse osmosis/ultrafiltration plus proton exchange membrane electrolysis, solar
Mustafa et al., 2023	Case study, sensitivity analysis	Najran, Saudi Arabia (arid)	Multi-generation, 2,709 kilograms hydrogen per year	Solar plus reverse osmosis plus fuel cell-based electrolysis [15]
Rehman et al., 2024	Case study, techno-economic modeling	Aqaba Gulf, Saudi Arabia (arid coastal)	8.2 million kilograms hydrogen per year	Onshore wind plus alkaline electrolysis [16]
Rezk et al., 2020	Feasibility, techno-economic analysis	NEOM City, Saudi Arabia (arid coastal)	4,895–5,530 kilograms hydrogen per year	Photovoltaic/fuel cell/battery storage hybrid, reverse osmosis, alkaline electrolysis [17]
Xu et al., 2025	Simulation, techno-economic analysis	Not specified (arid,	Not specified	Seawater membrane distillation plus

		coastal implied)		alkaline electrolysis [18]
Taroual et al., 2024	Techno-economic assessment	Morocco (six coastal regions)	20–40 tonnes hydrogen per year	Offshore wind/wave plus proton exchange membrane electrolysis [19]
Woods et al., 2022	Review, resource analysis	Australia (arid, national)	0.88 million tonnes hydrogen per year (potential)	Treated wastewater plus electrolysis (type not specified) [20]
León et al., 2023	Pre-feasibility, financial analysis	Chile (arid coastal)	1,000,000 kilograms hydrogen per year	Seawater reverse osmosis plus alkaline electrolysis, solar/wind [21]
Badruzzaman et al., 2025	Techno-economic, environmental analysis	Not specified (arid, urban)	1,904 kilograms hydrogen per hour (modeling)	Treated sewage effluent plus reverse osmosis/ultrafiltration plus proton exchange membrane electrolysis, solar/grid [22]

The reviewed studies show strong geographic concentration, with most conducted in Saudi Arabia and single cases in Portugal, Oman, Morocco, Australia, and Chile. Research is largely situated in arid contexts, often coastal or urban. System scales range from pilot to gigawatt level, with hydrogen outputs spanning kilograms per day to nearly a million tonnes annually. Water sources include seawater, wastewater, and treated effluents. Reverse osmosis dominates desalination, followed by ultrafiltration and membrane distillation. Electrolysis is evenly split between PEM and alkaline types, with one study using a fuel-cell electrolyzer. Energy inputs are diverse: mainly solar and wind, supplemented by wave, grid, and hybrid systems (Table 1).

Table 2 **-** Water Treatment System Performance

Study	**System Component**	**Performance Parameters**	**Efficiency Rates**	**Operating Conditions**
Azevedo et al., 2023	Seawater desalination (type not specified) plus proton exchange membrane electrolysis	No quantitative metrics mentioned	No mention found	Wind/solar, gigawatt-scale

Barghash et al., 2022	Treated effluent plus reverse osmosis/ultrafiltration plus proton exchange membrane electrolysis	1,500–50,000 kilograms hydrogen per day; 27–900 cubic meters per day water	No mention found	Solar, Oman
Mustafa et al., 2023	Reverse osmosis plus fuel cell-based electrolysis	2,709 kilograms hydrogen per year; 720 cubic meters purified water	58% solar use	Solar, Saudi Arabia
Rehman et al., 2024	Alkaline electrolysis	8,214,152 kilograms hydrogen per year; 7,335 hours per year operation	No mention found	160 megawatt wind, Saudi Arabia
Rezk et al., 2020	Reverse osmosis plus hybrid photovoltaic/fuel cell/battery storage plus alkaline electrolysis	4,895–5,530 kilograms hydrogen per year; 542,565 kilowatt-hours per year	No mention found	Photovoltaic/fuel cell/battery storage, Saudi Arabia
Xu et al., 2025	Membrane distillation plus alkaline electrolysis	49.65 kilograms per hour water consumption; 8,322 hours per year operation	70% (alkaline electrolysis)	Renewable
Taroual et al., 2024	Offshore wind/wave plus proton exchange membrane electrolysis	20–40 tonnes hydrogen per year; 14–20 megawatt electricity	13–18% (system), 62–89% (electrolyzer)	Morocco, hybrid renewables

Woods et al., 2022	Treated wastewater plus electrolysis	420,000 tonnes hydrogen per day (potential)	No mention found	Renewable, Australia
León et al., 2023	Reverse osmosis plus alkaline electrolysis	1,000,000 kilograms hydrogen per year; 2–3.1 cubic meters per hour water	No mention found	14–22 megawatt wind/solar, Chile
Badruzzaman et al., 2025	Reverse osmosis/ultrafiltration plus proton exchange membrane electrolysis	1,904 kilograms hydrogen per hour; 1,714 kilograms per hour water	60–80% (electrical), 56–73% (exergy)	Photovoltaic/solar thermal/parabolic trough collector/grid, 100 megawatt-hour electrolyzer

The reviewed studies demonstrate wide variation in system design. Water sources include seawater (three cases), wastewater, and treated effluents, though most are unspecified. Pretreatment methods range from reverse osmosis and ultrafiltration to membrane distillation. Electrolysis is evenly split between PEM and alkaline types, with one fuel-cell variant. Reported hydrogen outputs span from 1,500–50,000 kg/day to 420,000 tonnes/year, with highly diverse water demands and operating hours. Efficiency values vary widely (13–89%), and energy inputs include solar, wind, hybrid, and unspecified renewables. Geographically, Saudi Arabia dominates (three studies), with single cases in Oman, Morocco, Australia, and Chile (Table 2).

Table 3 **-** Electrolysis Integration and Efficiency

Study	**System Component**	**Performance Parameters**	**Efficiency Rates**	**Operating Conditions**
Azevedo et al., 2023	Proton exchange membrane electrolysis	No mention found	No mention found	Wind/solar, gigawatt-scale
Barghash et al., 2022	Proton exchange membrane electrolysis	1,500–50,000 kilograms hydrogen per day	No mention found	Solar
Mustafa et al., 2023	Fuel cell-based electrolysis	2,709 kilograms	58% solar use	Solar

		hydrogen per year		
Rehman et al., 2024	Alkaline electrolysis	8,214,152 kilograms hydrogen per year; 7,335 hours per year	No mention found	160 megawatt wind
Rezk et al., 2020	Alkaline electrolysis	4,895–5,530 kilograms hydrogen per year	No mention found	Photovoltaic/fuel cell/battery storage
Xu et al., 2025	Alkaline electrolysis	49.65 kilograms per hour water; 8,322 hours per year	70%	Renewable
Taroual et al., 2024	Proton exchange membrane electrolysis	20–40 tonnes hydrogen per year	62–89% (electrolyzer)	Offshore wind/wave
Woods et al., 2022	Electrolysis (type not mentioned)	420,000 tonnes hydrogen per day (potential)	No mention found	Renewable
León et al., 2023	Alkaline electrolysis	1,000,000 kilograms hydrogen per year	No mention found	Wind/solar
Badruzzaman et al., 2025	Proton exchange membrane electrolysis	1,904 kilograms hydrogen per hour	60–80% (electrical), 56–73% (exergy)	Photovoltaic/solar thermal/parabolic trough collector/grid

A technology-distribution analysis of electrolysis shows an equal predominance of the two main types-proton-exchange membrane (PEM) electrolyzers and alkaline electrolyzers-while a fuel-cell-type electrolyzer is mentioned in only one case. This balance indicates active technological competition and the absence of a single standard for integration with desalination (Table 3).

Studies report hydrogen production at multiple scales, from kilograms per hour to hundreds of thousands of tonnes annually, with operating times up to 8,322 hours. Efficiency values range widely (56–89%), reflecting technological and methodological differences. Energy supply configurations are diverse, including solar, wind, combined systems, and hybrid options. Regionally, Saudi Arabia dominates, with single studies from Portugal, Oman, Morocco, Australia, and Chile. Economically, most studies consider green hydrogen competitive, with reported costs between $1.37–6/kg, though one deems it unviable; parity with fossil-based hydrogen is seen as possible under favorable conditions.Additional related indicators were identified: annual revenue of 8.3–49.7 million Omani rials [23], electricity cost of $0.117–0.164 per kWh [17], and water cost of $1.28 per ton [18].

Renewable hydrogen deployment demands major investment in desalination, renewable energy, and storage, with feasibility highly dependent on local water, resource, and grid conditions. Despite limited empirical data and persistent challenges, large-scale adoption could deliver substantial environmental benefits.

Materials and methods

The modeled object is an off-grid coastal hybrid for western Kazakhstan: a photovoltaic (PV) installation, one or two Enercon E-82 E4 wind turbines (3 MW), a rectifier/inverter, a buffer battery bank (generic lead–acid), a 3 MW proton-exchange membrane (PEM) electrolyzer, 2,000 kg of hydrogen storage, and a reverse osmosis (RO) desalination unit specified as a deferrable load in HOMER Pro. The base scenario was chosen as the configuration most consistent with the “circular water” concept: a 5 MWp PV array + 1×E-82 (3 MW), because it combines a high share of renewable energy, significant generation curtailment, and the presence of RO as a flexible load. For the Base case: Annual electricity consumption of the electrolyzer: 5,125,030 kWh·yr^{-1}.

Equivalent full-load operating hours:

$$t_{el} = \frac{E_{el}}{P_{\text{ном}}} = \frac{5125030}{3000} \approx 1708 \frac{hour}{yr}$$

Average power:

$$P_{el} = \frac{E_{el}}{8760} \approx 585\ kW$$

Hydrogen output: ≈110,441 kg·yr^{-1} (Base; 105,109 kg·yr^{-1} for PV-only; 110,441 kg·yr^{-1} for Wind-only; 110,464 kg·yr^{-1} for PV+2×E-82).

LCOH: 11.9 USD·kg^{-1}; 10.4 USD·kg^{-1} (PV-only); 8.52 USD·kg^{-1} (Wind-only); 15.7 USD·kg^{-1} (PV+2×E-82).

Source utilization coefficients (Base, by installed capacity):

$$CF_{PV} = \frac{6522728}{5000 * 8760} \approx 14{,}9\%\ ,\quad CF_{wind} = \frac{10649665}{3000 * 8760} \approx 40{,}5\%$$

Energy conversion RO → volume of water (SEC = 3.0–4.5 kWh/m3)

Post-processing method for RO:

$$V_{RO}, yr = \frac{E_{RO}, yr}{SEC},\quad V_{RO}, day = \frac{V_{RO}, yr}{365},\quad V_{RO}, month = \frac{E_{RO}, month}{SEC}.$$

Results

Monthly aggregates of generation, electrolyzer demand, RO load, and curtailment were not directly provided in the outputs. Instead, seasonality was assessed qualitatively: the monthly diagram indicates that wind contributions are relatively uniform, where PV exhibits a pronounced summer peak. A strict quantitative breakdown is therefore not included. The currently installed RO capacity and dispatch profile absorb only a small fraction of the potential curtailment reduction; the reserve margin remains nearly an order of magnitude higher.

Annual RO energy: E_{RO}, year =729167 kWh.

Equivalent water output ($m^3 \cdot yr^{-1}$).

$$SEC = 3.0 \Rightarrow V_{year} = 3729609\, m^3 \cdot yr^{-1}$$
$$SEC = 3.5 \Rightarrow V_{year} = 3196808\, m^3 \cdot yr^{-1}$$
$$SEC = 4.0 \Rightarrow V_{year} = 2797207\, m^3 \cdot yr^{-1}$$
$$SEC = 4.5 \Rightarrow V_{year} = 2486406\, m^3 \cdot yr^{-1}$$

The share of actually loaded RO energy from the cutoff:

$$\left(\frac{E_{RO}}{E_{curt}}\right) * 100\% = 6{,}52\%$$

The specific water requirement for electrolysis is assumed at 9–10 $L \cdot kg^{-1}$ H_2 (including process losses). For the Base case (110,441 kg $H_2 \cdot yr^{-1}$):

$$V_{H2}, water \approx (0.009 - 0.010) \times 110441 = 994 - 1104\, m^3 \cdot yr^{-1}$$

Comparison with annual RO output is a large surplus-by a factor of 150–245 depending on SEC. This enables: (i) complete coverage of electrolyzer process water via desalination, (ii) diversion of excess RO water to local municipal/industrial demands or reserve storage, and (iii) incorporation of circular water use (e.g., reuse of RO flushing streams and auxiliary condensate) without risk of energy deficit. With SEC increasing from 3.0 to 4.5 $kWh \cdot m^{-3}$, annual RO output declines from 243,056 to 162,037 $m^3 \cdot yr^{-1}$ (−33%), while average daily yield decreases from 665.9 to 443.9 $m^3 \cdot d^{-1}$. The share of curtailed energy absorbed by RO is proportional to E_{RO} and does not depend on SEC; in the Base case it is fixed at 6.52% of generation.

*Scenarios***.** For PV-only and Wind-only cases, $E_{RO} \approx 0.729$ $GWh \cdot yr^{-1}$, but curtailment differs sharply (2.43 vs. 4.52 $GWh \cdot yr^{-1}$), resulting in markedly different RO absorption effects (E_RO/curtailment: 29.9% for PV-only vs. 16.1% for Wind-only). In the PV+2 × E-82 configuration, curtailment reaches its maximum (21.83 $GWh \cdot yr^{-1}$), while the contribution of the current RO to its absorption is minimal (3.34%), highlighting the need for either scaling up RO capacity or introducing alternative flexible loads/storage.

In the baseline hybrid configuration (PV 5 MW + 1 × Enercon E-82 E4, 3 MW), the annual generation reached 17,172,393 $kWh \cdot yr^{-1}$, of which PV contributed 6,522,728 $kWh \cdot yr^{-1}$ (38%) and wind 10,649,665 $kWh \cdot yr^{-1}$ (62%). Consumption was distributed as follows: electrolyzer – 5,125,103 $kWh \cdot yr^{-1}$ (87.5% of HOMER's "electric load"), RO – 729,167 $kWh \cdot yr^{-1}$ (12.5%), and miscellaneous AC load – 365 $kWh \cdot yr^{-1}$. "Curtailment" (i.e., unused surplus renewable energy) amounted to 11,188,827 $kWh \cdot yr^{-1}$, corresponding to

65.2% of total generation. The renewable fraction was 100%. Capacity factors were estimated as CF_PV ≈ 14.9% (6.52 GWh from 5 MW installed) and CF_wind ≈ 40.5% (10.65 GWh from 3 MW). Figure 1 summarizes the monthly generation profiles, electrolyzer and RO operation, and the share of curtailed energy.

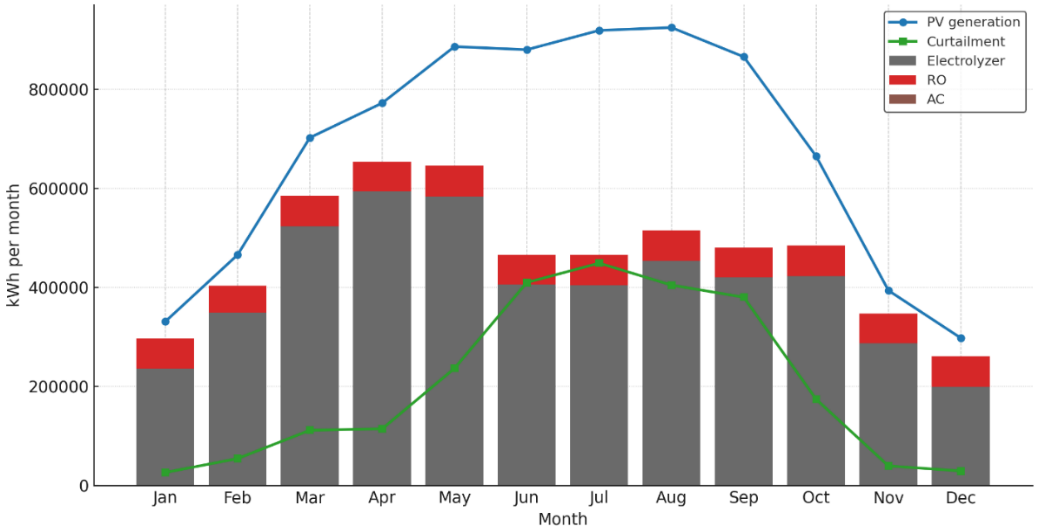

Figure 1 - Monthly energy balance (PV-only): PV generation, electrolyzer and RO consumption, curtailment (kWh/month)

The hybrid system produces 110,441 kg $H_2 \cdot yr^{-1}$, with stable electrolysis demand of ~46.4 $kWh \cdot kg^{-1}$ H_2. The electrolyzer operates at ~585 kW average load (CF ≈ 19.5% for 3 MW). Sensitivity analysis gives an LCOH of 8.52–15.7 $USD \cdot kg^{-1}$; the baseline case adopts 11.9 $USD \cdot kg^{-1}$ (Figure 2).

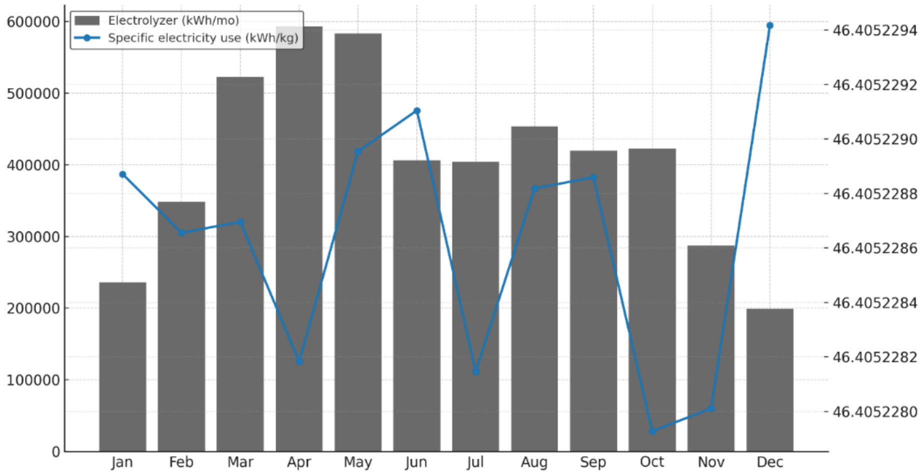

Figure 2 - H_2 production (kg/month) and specific electricity use (kWh/kg), monthly (PV-only)

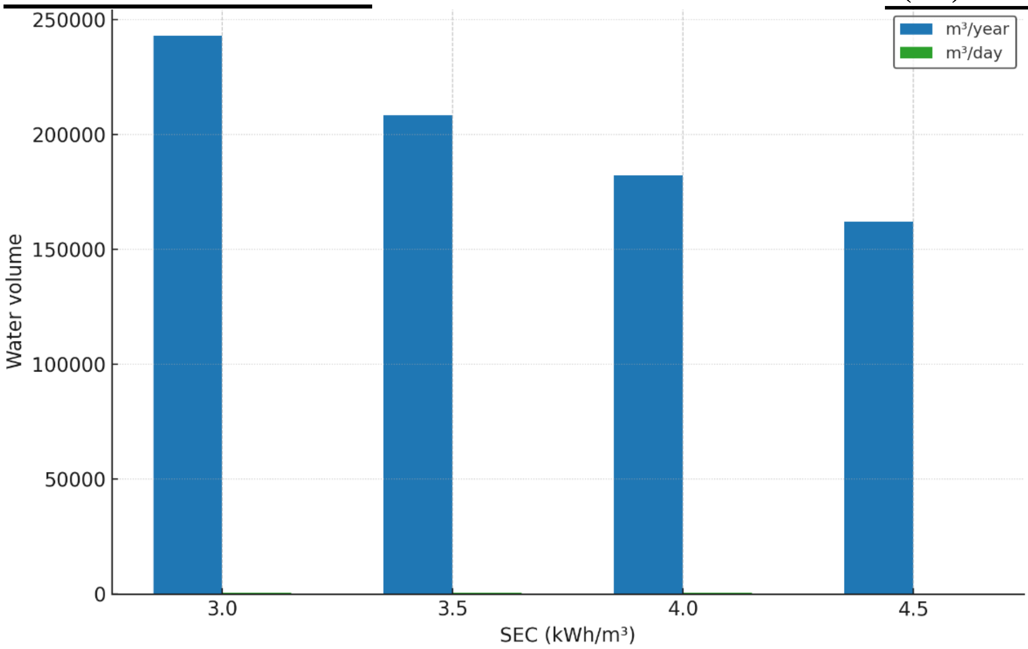

Figure 3 - RO water vs SEC (3.0–4.5 kWh/m³): annual (m³/year) and daily (m³/day) volumes

Hybrid case ($E_{RO,year}$ = 729,167 kWh·yr⁻¹):

$$SEC = 3.0: V_{year} \approx 243056\, m^3 \cdot yr^{-1}; \quad V_{day} \approx 665.9\, m^3 \cdot d^{-1}$$
$$SEC = 3.5: V_{year} \approx 208333\, m^3 \cdot yr^{-1}; \quad V_{day} \approx 570.8\, m^3 \cdot d^{-1}$$
$$SEC = 4.0: V_{year} \approx 182292\, m^3 \cdot yr^{-1}; \quad V_{day} \approx 499.4\, m^3 \cdot d^{-1}$$
$$SEC = 4.5: V_{year} \approx 162037\, m^3 \cdot yr^{-1}; \quad V_{day} \approx 443.9\, m^3 \cdot d^{-1}$$

For the PV-only scenario (based on the hourly output, $E_{RO,year}$=728,702 kWh·yr⁻¹), the monthly breakdown can be presented analogously, with water production volumes scaled by SEC to capture seasonal variations in PV-driven operation.

For SEC = 3.5 kWh·m⁻³, the modeled RO system delivers an average output of approximately 17.35 thousand m³ per month. The seasonal amplitude is modest, at around 11.2%, with the minimum production observed in February (15.8 thousand m³) and the maximum in March (17.76 thousand m³). This relatively low variability indicates that the hybrid PV–wind configuration provides a stable water yield across the year, reinforcing the reliability of RO as a flexible sink for curtailed renewable energy.

At the current RO capacity:

- **PV-only**: annual RO consumption $E_{RO,year}$=728,702 kWh; curtailment = 2,433,308 kWh ⇒ RO absorbs ≈29.95% of curtailed energy.
- **Wind-only**: curtailment ≈4,519,613 kWh ⇒ RO absorbs ≈16.1%.
- **Hybrid (Base)**: curtailment = 11,188,827 kWh ⇒ RO absorbs ≈6.5%.

Discussion

This demonstrates that while the present RO load substantially offsets PV-only curtailment, its relative impact diminishes as total curtailment grows in wind-dominated and hybrid configurations, highlighting the need for scalable RO capacity to more effectively mitigate idle renewable generation.

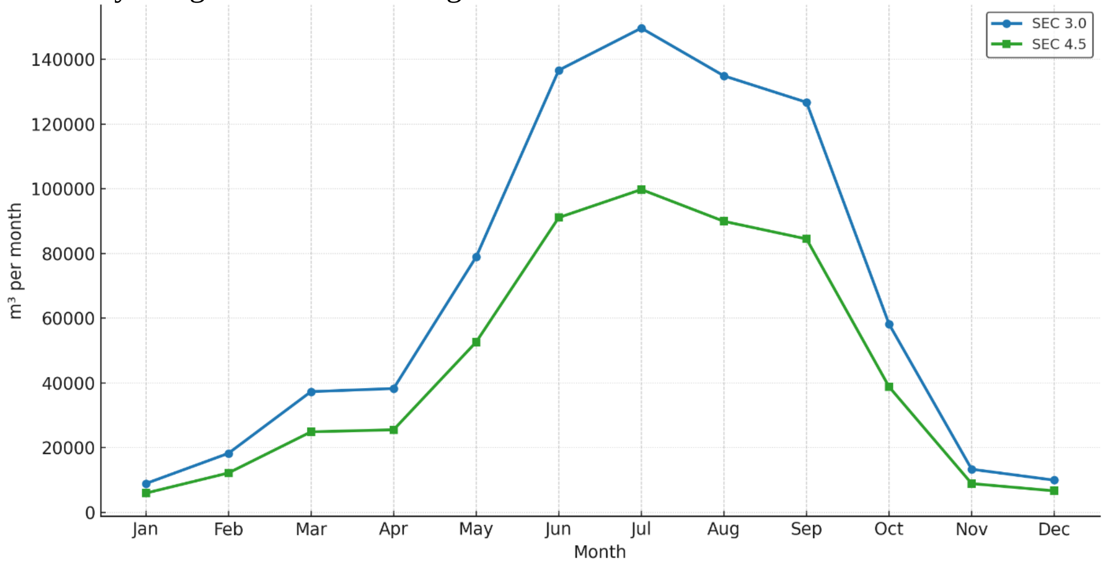

Figure 4 - Curtailment→water potential (m^3/month) at SEC 3.0 and 4.5 (PV-only)

RO scaling potential ranges from 2.49–3.73 million $m^3 \cdot yr^{-1}$ depending on SEC, but only ~0.54–0.81 million $m^3 \cdot yr^{-1}$ in PV-only scenarios. Seasonal analysis shows PV peaking in summer and wind remaining stable, suggesting that curtailment can be reduced by shifting RO loads to surplus periods. Prioritizing electrolyzers over RO ensures hydrogen output while excess energy is directed to water production.

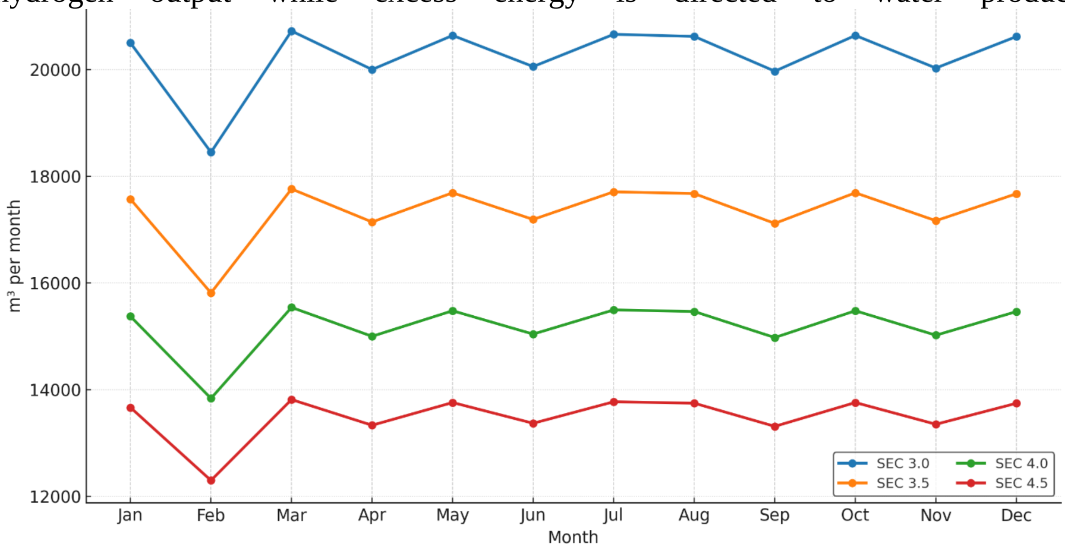

Figure 5 - Monthly RO water by SEC (3.0–4.5 kWh/m^3) (PV-only)

At 10 L H_2O per kg H_2, electrolyzer demand is ~1,104 $m^3 \cdot yr^{-1}$, whereas RO yields 162,000–243,000 $m^3 \cdot yr^{-1}$ (147–189× higher), ensuring surplus water supply (Figure 5).

PEM fuel cell condensation offsets ~90–99% of demand, achieving near-complete circularity and leaving most RO output available for external use. Higher SEC reduces yield by one-third, but scaled RO enhances curtailment-to-water conversion and indirectly improves hydrogen economics, with modeled LCOH spanning $8.5–15.7/kg (Figure 6).

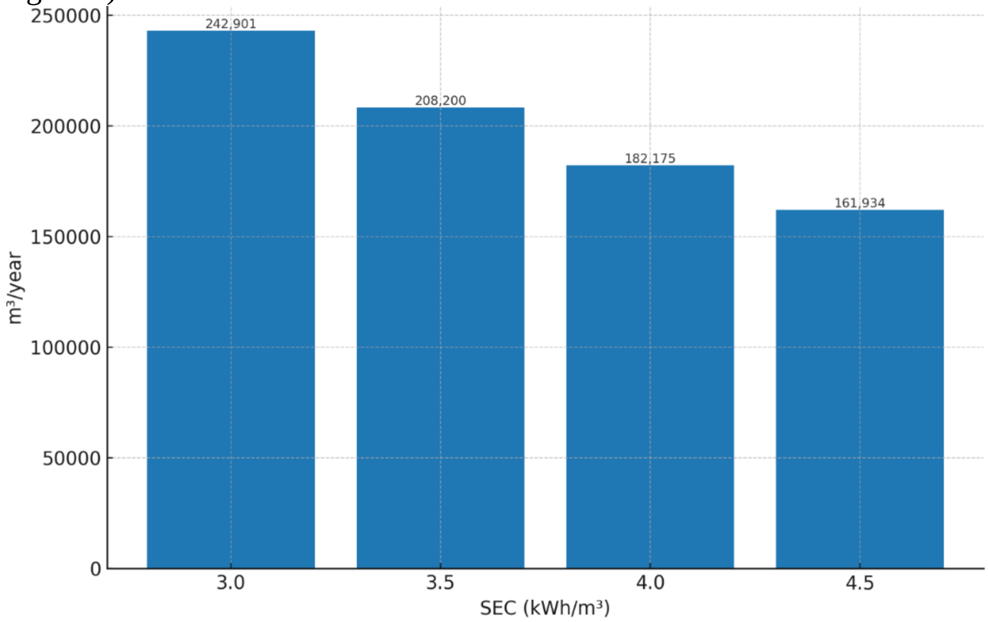

Figure 6 - Sensitivity to SEC: annual RO water (m^3/year)

The assessment of brine quality and disposal scenarios falls outside the scope of the present modeling. Nevertheless, the conclusion remains robust: flexible RO substantially reduces curtailment and generates a surplus water resource, with virtually no competition for water with electrolysis-an important advantage in the arid coastal context of Mangystau.

Conclusion

The “SWRO → deionization → PEM electrolysis → recirculation/reuse” chain is technologically coherent and well-suited to Mangystau, combining mature membrane and electrochemical technologies and enabling follower-mode operation under variable renewable profiles. Evidence from coupling renewable desalination with hydrogen production indicates that PEM systems offer strong dynamic controllability and product purity, facilitating integration with VRE. Target electrolyzer feedwater quality is achievable via two routes: (i) seawater desalination followed by deionization and (ii) polishing of treated wastewater; in the latter case, two-stage membrane trains can deliver conductivity below 5 µS/cm. For comparable daily H_2 output, a wind-plus-SWRO intermittent configuration yields the lowest CAPEX, making it a promising choice for a demonstration project. The water footprint can be further reduced through local recirculation between the electrolyzer and ancillary consumers/cooling systems.

Acknowledgments

This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR24992964).

REFERENCES

[1] Kurishbaev, A., Gabdullin, M., Amanzholova, R., Em, T., Sagin, J., Sarsekova, D., Absametov, M. (2024). The importance of expanding research on the serpentinization of ophiolite rocks by natural “white” hydrogen for Kazakhstan. *Herald of the Kazakh-British technical university*, *21*(3), 343–353. https://doi.org/10.55452/1998-6688-2024-21-3-343-353

[2] Koibakova, S. E., Kenzhetaev, G. J., Syrlybekkyzy, S., Tarasenko, G., Suleimenova, B., & Taizhanova, L. (2021). Experimental studies of the efficiency of a solar system, including a passive water heater and an active seawater distiller. *Heliyon*, *7*(2), e05938. https://doi.org/10.1016/j.heliyon.2021.e05938

[3] Castagnini, M., Rinaldi, M., Pojatar, D., & Castagnini, M. (n.d.). Green Hydrogen for Oil Industry Green Mobility. Retrieved from https://dx.doi.org/10.2118/216804-MS

[4] Muratova, M., Sadri, H., Medeubayeva, Z., & Issayeva, A. (2025). The EU and Kazakhstan in the Latest Geopolitical and Geoeconomic Conditions: New Dimensions of Partnership. *Journal of Eurasian Studies*, *16*(1), 20–31. https://doi.org/10.1177/18793665231215799

[5] Mirovyye pokazateli razvitiya, DataBank. Polucheno 2 sentyabrya 2025 g., https://databank.worldbank.org/source/world-development-indicators#.[World Development Indicators, DataBank. Retrieved September 2, 2025, from https://databank.worldbank.org/source/world-development-indicators#.

[6] Mezhdunarodnoye energeticheskoye agentstvo (IEA). Baza dannykh po energeticheskoy statistike – instrumenty dannykh. Mezhdunarodnoye energeticheskoye agentstvo. Polucheno 2 sentyabrya 2025 g., https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser. [The International Energy Agency (IEA). Energy Statistics Data Browser – Data Tools. The International Energy Agency. Retrieved September 2, 2025, from https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser.

[7] Mezhdunarodnaya torgovaya administratsiya. Rukovodstvo po energeticheskim resursam – Kazakhstan – vozobnovlyayemaya energetika. Polucheno 2 sentyabrya 2025 g., https://www.trade.gov/energy-resource-guide-kazakhstan-renewable-energy. [The International Trade Administration. Energy Resource Guide - Kazakhstan - Renewable Energy. Retrieved September 2, 2025, from https://www.trade.gov/energy-resource-guide-kazakhstan-renewable-energy.

[8] Apolinário, R., & Castro, R. (2024). Solar-Powered Desalination as a Sustainable Long-Term Solution for the Water Scarcity Problem: Case Studies in Portugal. *Water*, *16*(15), 2140. https://doi.org/10.3390/w16152140

[9] Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S., & Ulgiati, S. (2018). Life Cycle Assessment and Water Footprint of Hydrogen Production Methods:

From Conventional to Emerging Technologies. *Environments*, *5*(2), 24. https://doi.org/10.3390/environments5020024

[10] Janowitz, D., Groche, S., Yüce, S., Melin, T., & Wintgens, T. (2022). Can Large-Scale Offshore Membrane Desalination Cost-Effectively and Ecologically Address Water Scarcity in the Middle East? *Membranes*, *12*(3), 323. https://doi.org/10.3390/membranes12030323

[11] Verbruggen, A., Yermekova, G., & Baigarin, K. (2025). Dubious Promises of Hydrogen Energy in a Climate-Constrained World. *Energies*, *18*(3), 491. https://doi.org/10.3390/en18030491

[12] Sansyzbayeva, G., Temerbulatova, Z., Aknur, Z., & Ashirbekova, L. (2020). Evaluating the transition to green economy in Kazakhstan: A synthetic control approach. *Journal of International Studies*, *13*(1), 324–341. https://doi.org/10.14254/2071-8330.2020/13-1/21

[13] Barghash, H., Al Farsi, A., Okedu, K. E., & Al-Wahaibi, B. M. (2022). Cost benefit analysis for green hydrogen production from treated effluent: The case study of Oman. *Frontiers in Bioengineering and Biotechnology*, *10*, 1046556. https://doi.org/10.3389/fbioe.2022.1046556

[14] d'Amore-Domenech, R., Santiago, Ó., & Leo, T. J. (2020). Multicriteria analysis of seawater electrolysis technologies for green hydrogen production at sea. *Renewable and Sustainable Energy Reviews*, *133*, 110166. https://doi.org/10.1016/j.rser.2020.110166

[15] Mustafa, J., Alqaed, S., Almehmadi, F. A., Malekshah, E. H., & Sharifpur, M. (2024). Effect of economic and environmental parameters on multi-generation of electricity, water, heat, and hydrogen in Saudi Arabia: A case study. *International Journal of Hydrogen Energy*, *52*, 585–598. https://doi.org/10.1016/j.ijhydene.2023.07.035

[16] Wind to Hydrogen: A Case Study in Aqaba Gulf | IEEE Conference Publication | IEEE Xplore. (n.d.). Retrieved September 3, 2025, from https://ieeexplore.ieee.org/document/10799578

[17] Rezk, H., Alghassab, M., & Ziedan, H. A. (2020). An Optimal Sizing of Stand-Alone Hybrid PV-Fuel Cell-Battery to Desalinate Seawater at Saudi NEOM City. *Processes*, *8*(4), 382. https://doi.org/10.3390/pr8040382

[18] Xu, X., Zhao, Z., Song, C., Xu, L., & Zhang, W. (2025). Seawater Membrane Distillation Coupled with Alkaline Water Electrolysis for Hydrogen Production: Parameter Influence and Techno-Economic Analysis. *Membranes*, *15*(2), 60. https://doi.org/10.3390/membranes15020060

[19] Taroual, K., Nachtane, M., Rouway, M., Tarfaoui, M., Faik, A., Mînzu, V., … Saifaoui, D. (2024). Marine Renewable-Driven Green Hydrogen Production toward a Sustainable Solution and a Low-Carbon Future in Morocco. *Journal of Marine Science and Engineering*, *12*(5), 774. https://doi.org/10.3390/jmse12050774

[20] Woods, P., Bustamante, H., & Aguey-Zinsou, K.-F. (2022). The hydrogen economy - Where is the water? *Energy Nexus*, *7*, 100123. https://doi.org/10.1016/j.nexus.2022.100123

[21] León, M., Silva, J., Ortíz-Soto, R., & Carrasco, S. (2023). A Techno-Economic Study for Off-Grid Green Hydrogen Production Plants: The Case of Chile. *Energies*, *16*(14), 5327. https://doi.org/10.3390/en16145327

[22] Badruzzaman, A., Karagoz, S., & Eljack, F. (2025). Sustainable-green hydrogen production through integrating electrolysis, water treatment and solar energy. *Frontiers in Chemical Engineering*, *7*, 1526331. https://doi.org/10.3389/fceng.2025.1526331

[23] Barghash, H., Al Farsi, A., Okedu, K. E., & Al-Wahaibi, B. M. (2022). Cost benefit analysis for green hydrogen production from treated effluent: The case study of Oman. *Frontiers in Bioengineering and Biotechnology*, *10*, 1046556. https://doi.org/10.3389/fbioe.2022.1046556

Рамазан А. Қ., Тайжанова Л.С., Сырлыбекқызы С.

АРИДТІ ЖАҒАЛАУ АЙМАҚТАРЫНА АРНАЛҒАН ТӨМЕН КӨМІРТЕКТІ ТҰЩЫЛАНДЫРУ ТЕХНОЛОГИЯЛАРЫН МОДЕЛЬДЕУ ЖӘНЕ ЭКОЛОГИЯЛЫҚ БАҒАЛАУ

Аңдатпа. Мақала Батыс Қазақстанның аридті теңіз жағалауы жағдайында жасыл сутегі өндіру үшін жаңартылатын энергиямен қамтамасыз етілетін теңіз суын кері осмос (SWRO) және электролизді біріктіретін айналымдық су жүйесінің іске асырылуын және архитектурасын қарастырады. Әдіснама технологиялық және технико-экономикалық шешімдерге сыни шолу жасауды, энергиямен жабдықтау конфигурацияларын (күн/жел; үздіксіз/үзілісті жұмыс) салыстыруды және электролизерлерге арналған су дайындау маршруттарын (тұзсыздандырылған теңіз суы және тазартылған шайынды суды қосымша тазарту) талдауды қамтиды. Зерттеу SWRO мен протоналмастырғыш мембраналы (PEM) электролизді біріктіру техникалық жүзеге асатынын; қажетті коректік су сапасы мембраналық полишинг тізбектері арқылы қамтамасыз етілетінін; желмен коректенетін үзілісті режим энергия сақтау сыйымдылықтарына қажеттілікті азайтып, күрделі шығындарды төмендететінін көрсетеді. Практикалық маңызы – аймақтың су қауіпсіздігін және декарбонизацияны күшейту, сондай-ақ сутегіні экспорттау әлеуеті. Жұмыс Маңғыстау үшін пилоттық бағыттар мен масштабтау мәселелерін айқындайды.

Кілт сөздер: Төменкөміртекті технологиялар; Тұщыландыру; Жасыл сутегі; Жаңартылатын энергия; Кері осмос; Су айналымы жүйелері; Аридті жағалау аймақтары; Маңғыстау облысы; Күн фотоэлектр жүйелері; Жел энергиясы.

Рамазан А. Қ., Тайжанова Л.С., Сырлыбекқызы С.

МОДЕЛИРОВАНИЕ И ЭКОЛОГИЧЕСКАЯ ОЦЕНКА НИЗКОУГЛЕРОДНЫХ ТЕХНОЛОГИЙ ОПРЕСНЕНИЯ ДЛЯ ЗАСУШЛИВЫХ ПРИБРЕЖНЫХ РЕГИОНОВ

Аннотация. Статья исследует осуществимость и архитектуру циркуляционной водной системы, сочетающей возобновляемо-энергетическое обратное осмосное опреснение (SWRO) и электролиз для производства «зелёного» водорода в засушливой прибрежной зоне Западного Казахстана. Методология включает критический обзор технологических и технико-экономических решений, сопоставление вариантов энергоснабжения (солнечная/ветровая генерация, непрерывный/прерывистый режимы), а также анализ путей подготовки воды для электролизёров (опреснение морской воды и полирование очищенных сточных вод). Показано, что интеграция SWRO и PEM-электролиза технически выполнима; требуемое качество питательной воды достижимо мембранными схемами доочистки; прерывистая работа, питаемая ветроэнергетикой, снижает капитальные затраты благодаря меньшим требованиям к накопителям. Практическое значение состоит в повышении водной безопасности и декарбонизации региона при одновременном формировании экспортного потенциала водорода; предложены направления для пилотной демонстрации и масштабирования.

Ключевые слова: Низкоуглеродные технологии; Опреснение; Зелёный водород; Возобновляемая энергия; Обратный осмос; Системы циркулярного водопользования; Засушливые прибрежные регионы; Мангистауская область; Солнечные фотоэлектрические системы; Ветроэнергетика.