DOI 10.58880/DKU.2026.02.04
STI Code 87.26.11
UDC 620.9:556

GREEN HYDROGEN AND THE PRICE OF WATER: A SCENARIO ASSESSMENT FOR THE CASPIAN REGION OF KAZAKHSTAN

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Abstract

This article examines the water implications of large-scale green hydrogen production in the Caspian region of Kazakhstan. The study focuses on Mangystau Region and uses the publicly announced scale of the Hyrasia One project as a case study. A screening-level scenario method is applied to estimate annual and daily water demand at three water-use intensities: 9, 15, and 20 litres per kilogram of hydrogen. At the planned output of up to 2 million tonnes of hydrogen per year, the estimated demand ranges from 18 to 40 million m³ annually, or approximately 49,000–110,000 m³ per day. The central scenario of 30 million m³ per year is higher than the design capacity of the 50,000 m³/day Kenderli desalination plant and therefore cannot be treated as a minor local utility demand. At the same time, the electricity required for seawater reverse osmosis would represent only a small share of the renewable electricity announced for the hydrogen complex. This means that the main constraints are not only energy costs, but also water allocation, intake and brine-discharge impacts, infrastructure timing, and coordination with public water supply. The article concludes that hydrogen planning in western Kazakhstan should be linked to integrated water resources management, a dedicated non-potable water supply, environmental monitoring, and staged project development.

Keywords: green hydrogen, water resources, electrolysis, Hyrasia One, Mangystau, Caspian Sea, desalination, water scarcity, IWRM, Kazakhstan.

1. Introduction

Green hydrogen has moved from a mainly experimental technology to an important part of industrial and climate policy. It is expected to support decarbonisation in sectors where direct electrification is difficult, including fertiliser production, steel, shipping, and some forms of long-distance transport. However, recent international experience also shows that hydrogen development is slower and more uncertain than many early announcements suggested. High production costs, uncertain demand, limited transport infrastructure, and delays in final investment decisions remain important barriers [1]. For this reason, green hydrogen projects should be assessed not only by their technical potential, but also by the local resources and institutions needed for implementation.

Water is one of these resources. The chemical minimum for electrolysis is close to 9 litres of demineralised water per kilogram of hydrogen. The actual demand of a production complex is higher because raw water must be treated and because water may also be needed for cooling and auxiliary processes. IRENA and Bluerisk estimate average water consumption for proton exchange membrane electrolysis at about 17.5 litres per kilogram, although the final value depends strongly on technology and cooling design [2]. Therefore, the global water footprint of hydrogen may appear modest, while the local effect can still be serious when a project is located in an arid region [2, 3].

This issue is particularly relevant for western Kazakhstan. Mangystau has strong wind and solar resources and access to the Caspian coast, but it also has limited natural freshwater. The region depends on water transported through the Astrakhan–Mangyshlak pipeline, seawater desalination, and local groundwater sources. Public investment in new desalination capacity is mainly intended to reduce shortages for the population and existing economic activities [7, 8]. A new industrial water user at the scale of a large hydrogen complex may therefore create pressure even when seawater, rather than drinking water, is selected as the source.

The purpose of this study is to estimate the water demand associated with the announced production scale of Hyrasia One and to compare the results with selected indicators of regional water infrastructure. The study answers three questions: (1) how much water may be required at different water-use intensities; (2) how this demand compares with recently announced water-supply capacities in Mangystau; and (3) which water-governance and environmental conditions should be included in hydrogen planning. The contribution of the article is a transparent screening calculation for a specific Kazakhstani case. It does not replace a detailed feasibility study, but it provides an evidence-based starting point for discussion.

2. Study Context and Research Gap

2.1. Hyrasia One and the energy potential of Mangystau

Hyrasia One is planned as a large wind–solar–hydrogen complex in southwest Kazakhstan. According to the project developer, the concept includes approximately 40 GW of wind and solar capacity, around 20 GW of electrolysers, and production of up to 2 million tonnes of green hydrogen per year. The hydrogen may also be converted into up to 11 million tonnes of green ammonia for domestic use and export [5, 6]. The scale is important: it would place the project among the largest hydrogen developments announced worldwide.

Mangystau has several advantages for this type of project: large areas with renewable-energy potential, existing energy and industrial experience, and proximity to the Caspian Sea. Kazakhstan has also created a policy basis for renewable-energy growth, which is necessary because green hydrogen depends on access to low-carbon electricity [14]. Nevertheless, the presence of renewable resources does not automatically mean that a project is economically or environmentally sustainable. The water supply, desalination system, export chain, conversion facilities, certification requirements, and long-term buyers must develop together.

2.2. Regional water constraints

Mangystau is one of the regions of Kazakhstan where water supply has required continuous infrastructure expansion. In 2023, the capacity of the Astrakhan–Mangyshlak water pipeline was increased from 110,000 to 170,000 m^3/day, providing an additional 60,000 m^3/day for consumers in Atyrau and Mangystau [7]. The same government programme included a 50,000 m^3/day seawater desalination plant at Kenderli and reconstruction of the Caspiy desalination plant to reach 40,000 m^3/day [7]. KazMunayGas reports that population water consumption in the service area of the main pipeline grows by approximately 4–5% per year [8]. These figures show that new capacity is being developed in response to existing social and industrial demand rather than as unused reserve capacity for hydrogen production.

The environmental context is also changing. Recent climate research projects a continued decline in the level of the Caspian Sea during the twenty-first century, although the magnitude depends on the climate scenario and model assumptions [11]. A decline of only 5–10 metres could already produce major impacts on coastal ecosystems, protected areas, and infrastructure [12]. This does not mean that desalination should be rejected, but it means that seawater intake and brine discharge cannot be treated as a simple technical detail.

2.3. Research gap

Most international discussions of hydrogen and water provide global or national averages. Such averages are useful for showing that electrolysis will not dominate total global water consumption, but they do not answer the local planning question. For Mangystau, the relevant issue is whether a new water demand of tens of thousands of cubic metres per day can be added without reducing water security for residents, agriculture, ecosystems, and existing industries. The current article addresses this gap by linking public information on the Hyrasia One production target to public information on regional water infrastructure.

3. Materials and Methods

3.1. Research design and data sources

The study uses a case-study and scenario-assessment approach. The production target and main technical scale of Hyrasia One are taken from official project publications [5, 6]. Regional infrastructure indicators are taken from the Government of Kazakhstan and KazMunayGas [7, 8]. Water-intensity assumptions are based on international technical and scientific literature on electrolysis and hydrogen production [2–4]. Desalination energy assumptions are based on recent research on seawater reverse osmosis [10]. The environmental discussion uses peer-reviewed studies of global brine production and Caspian Sea level decline [9, 11, 12].

3.2. Scenario assumptions

Three water-use intensities were selected. The minimum scenario uses 9 L/kg H_2 and represents the approximate stoichiometric requirement for the electrolyser feed. The central scenario uses 15 L/kg H_2 and represents an efficient industrial configuration with additional treatment and auxiliary demand. The high scenario uses 20 L/kg H_2 as a conservative screening value. These values cover the range used in the literature and are centred around the average value reported by IRENA and Bluerisk for PEM electrolysis [2].

Table 1 - Main assumptions used in the scenario assessment

Parameter	Minimum scenario	Central scenario	High scenario
Hydrogen output	2.0 Mt/year	2.0 Mt/year	2.0 Mt/year
Water-use intensity	9 L/kg H_2	15 L/kg H_2	20 L/kg H_2
SWRO electricity	2.5–4.0 kWh/m³	2.5–4.0 kWh/m³	2.5–4.0 kWh/m³
Operating days	365	365	365

Annual water demand was calculated as W = H × I / 1,000, where W is water demand in m³/year, H is hydrogen output in kg/year, and I is water-use intensity in litres per kilogram. Daily demand was calculated by dividing annual demand by 365. Indicative desalination electricity demand was calculated by multiplying the required water volume by 2.5–4.0 kWh/m³, the range reported for modern seawater reverse-osmosis systems [10].

3.3. Limitations

This is a screening-level assessment based on public data. It does not include a site-specific water balance, seasonal operation, detailed electrolyser type, cooling technology, water-recovery rate, salinity at the intake point, brine chemistry, pipeline distance, or final environmental-impact assessment. The calculation also does not assume that existing public water facilities can supply the hydrogen project. Their capacities are used only as a scale comparison. A project-level feasibility study may produce lower or higher values depending on design choices.

4. Results

4.1. Estimated water demand

At the announced production target of 2 million tonnes of hydrogen per year, the minimum theoretical demand is approximately 18 million m³/year. The central scenario gives 30 million m³/year, and the high scenario gives 40 million m³/year. On a daily basis, the range is approximately 49,000–110,000 m³/day.

Table 2 - Estimated water and desalination electricity requirements at 2 Mt H_2/year

Scenario	Water intensity (L/kg)	Water demand (million m³/year)	Water demand (m³/day)	Indicative SWRO electricity (GWh/year)
Minimum	9	18	49,315	45–72
Central	15	30	82,192	75–120
High	20	40	109,589	100–160

The results show why the statement that hydrogen needs “millions of cubic metres of water” is not sufficiently precise for regional planning. The daily demand is of the same order as major water-supply projects in Mangystau. The minimum scenario is almost equal to the entire design capacity of the Kenderli desalination plant (50,000 m³/day). The central scenario is about 1.6 times that capacity, while the high scenario is about 2.2 times greater. The central scenario is also larger than the additional 60,000 m³/day created by the expansion of the Astrakhan–Mangyshlak pipeline [7].

These comparisons do not mean that the project should use drinking-water infrastructure. On the contrary, they show that a dedicated source and separate infrastructure are necessary. Even the theoretical minimum is too large to be treated as a small additional demand that can be absorbed by the existing regional system without planning.

4.2. Desalination energy is not the only constraint

Using the assumed seawater reverse-osmosis energy range, desalination for the three scenarios would require approximately 45–160 GWh/year. The Hyrasia One concept refers to renewable electricity generation of about 120 TWh/year [6]. Therefore, the electricity used for desalination would be approximately 0.04–0.13% of the announced renewable generation. This calculation suggests that desalination energy consumption alone is unlikely to be the main barrier at the full project scale.

However, this result should not be interpreted as evidence that desalination is environmentally neutral. A plant must also include seawater intake, pretreatment, demineralisation, pumping, storage, and brine management. Global desalination facilities produce large volumes of concentrated brine, and environmental effects depend on salinity, chemicals, discharge design, currents, and local ecosystem sensitivity [9]. For the Caspian Sea, a landlocked water body facing long-term level decline and ecological pressure, site-specific modelling and monitoring are especially important [11, 12].

4.3. Water demand may influence project location and phasing

The scenario results support a staged approach. A first production phase would require less water and would allow actual data to be collected on water quality, desalination performance, brine dispersion, and ecosystem response. Expansion to the full 2 Mt/year target should be conditional on the availability of dedicated water infrastructure and compliance with environmental limits. This would reduce the risk that the hydrogen project develops faster than the supporting water system.

5. Discussion

5.1. Water allocation and Integrated Water Resources Management

The main policy question is not simply whether there is enough seawater in the Caspian Sea. The question is how water abstraction, treatment, discharge, and infrastructure are governed in relation to other users and ecosystems. Integrated Water Resources Management (IWRM) is useful because it considers water, land, economic development, and stakeholder interests together rather than as separate sectors [13]. For hydrogen development in Mangystau, this principle should be applied at both project and regional levels.

A practical IWRM framework for a large hydrogen project should include:

- a legal guarantee that potable water allocated to households will not be displaced by hydrogen production;
- a dedicated water balance covering intake, treatment losses, process use, reuse, and discharge;
- assessment of cumulative impacts together with municipal desalination plants, oil and gas facilities, and future industrial projects;
- publication of water-use and water-quality indicators throughout project operation;
- participation of local authorities, water utilities, scientists, residents, and environmental organisations in key decisions.

Water pricing is also important. A low tariff may not reflect scarcity, infrastructure costs, or environmental risks. At the same time, a very high tariff alone will not protect ecosystems if environmental limits and monitoring are weak. The economic value of water should therefore be combined with clear allocation rules and ecological standards [15].

5.2. Alternative sources and efficiency options

Dedicated seawater desalination is the most visible option because the project is near the Caspian coast. Nevertheless, it should be compared with other sources. Treated municipal or industrial wastewater may provide part of the demand after advanced treatment. Process-water reuse and closed-loop cooling can also reduce total consumption. KazMunayGas already reports projects aimed at reducing freshwater withdrawal and increasing wastewater reuse in the region [8]. The available volumes and quality are not yet sufficient for a reliable project calculation, but these options should be assessed before new abstraction is approved.

The technology choice also matters. Water consumption can be reduced through high recovery in treatment systems, dry or hybrid cooling, leakage control, and reuse of condensate where technically possible. For this reason, the project should publish both water withdrawal and water consumption. Withdrawal describes the total volume taken from a source, while consumption describes the part not returned to the same water system. Using only one indicator can give an incomplete picture.

5.3. Economic and geoeconomic uncertainty

Water is an important constraint, but it is not the only uncertainty surrounding Hyrasia One. Large-scale green hydrogen remains more expensive than conventional hydrogen in many markets, and international projects face uncertain demand, regulatory changes, and slow infrastructure development [1]. For an export-oriented project in Kazakhstan, the value chain may include conversion to ammonia, storage, port handling, shipping across the Caspian, further transport through the Caucasus or other routes, and certification for the final market. Each additional stage affects cost, energy use, and commercial risk.

This makes it necessary to avoid two opposite conclusions. The first is that water scarcity makes green hydrogen impossible in Mangystau. The calculations do not support this, because dedicated desalination can technically provide the required water and its electricity demand is small relative to the announced renewable generation. The second conclusion is that desalination completely solves the water problem. This is also incorrect, because infrastructure, brine discharge, local ecosystems, social priorities, and institutional coordination remain significant. The project can be sustainable only when these conditions are included in the design and cost from the beginning.

5.4. Policy recommendations for Kazakhstan

Based on the scenario assessment, the following measures are recommended:

- Require a project-specific water strategy before approval of the full production scale, including seasonal and cumulative water balances.
- Develop dedicated non-potable water infrastructure so that the hydrogen project does not compete directly with household supply.
- Make project expansion conditional on verified performance of desalination, reuse, and brine-management systems.

- Include Caspian Sea level decline and coastline change in the design of intake, outfall, port, and pipeline infrastructure.
- Use transparent monitoring and public reporting for water withdrawal, consumption, water quality, brine salinity, and ecological indicators.
- Assess export demand and infrastructure together with water and energy planning, rather than approving each component separately.

6. Conclusion

The Caspian region of Kazakhstan has strong potential for renewable energy and green hydrogen, but this potential is located in a water-scarce environment. Using the announced Hyrasia One target of up to 2 million tonnes of hydrogen per year, this study estimates water demand of 18–40 million m^3/year. The central estimate is 30 million m^3/year, or about 82,000 m^3/day. This is larger than the design capacity of the Kenderli desalination plant and shows that water supply for hydrogen must be treated as major industrial infrastructure.

The analysis also gives a more balanced view of desalination. Its electricity demand would be small compared with the renewable generation announced for the project, so energy consumption is not necessarily the decisive limitation. The more difficult issues are the timing and cost of dedicated infrastructure, protection of public water supply, brine discharge, ecological sensitivity of the Caspian Sea, and coordination between water and energy policy.

Green hydrogen development in Mangystau is therefore possible, but it should be conditional rather than automatic. A dedicated water source, staged implementation, water reuse, environmental monitoring, and an IWRM-based governance framework should be included from the earliest design stage. Future research should use project-specific engineering data and regional datasets to model seasonal water availability, desalination recovery, brine dispersion, wastewater reuse potential, and the full economic cost of the hydrogen–water system.

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РЕЗЮМЕ

ЗЕЛЁНЫЙ ВОДОРОД И ЦЕНА ВОДЫ: ВЫЗОВЫ КАСПИЙСКОГО РЕГИОНА КАЗАХСТАНА

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В статье рассматриваются перспективы развития энергетики зелёного водорода в западных регионах Казахстана с особым акцентом на ограниченность водных ресурсов. Актуальность исследования обусловлена растущим мировым интересом к водороду как ключевому элементу стратегий декарбонизации. Цель работы — оценить взаимосвязь между производством водорода и обеспеченностью водой в засушливых районах. Методологическая база включает аналитический обзор, сравнительный анализ и количественную оценку водопотребления в процессах электролиза. Результаты показывают, что крупномасштабное производство водорода требует значительных водных ресурсов, которые могут стать ограничивающим фактором в регионах с существующим водным дефицитом, таких как Прикаспий. В исследовании также выявлены экологические и экономические ограничения опреснения как альтернативного источника воды. Сделан вывод о том, что устойчивое развитие водородной энергетики в Казахстане требует интеграции с системами управления водными ресурсами и согласованных политических подходов.

Ключевые слова: зелёный водород, водные ресурсы, электролиз, Прикаспийский регион, Казахстан, опреснение, возобновляемая энергия, дефицит воды, энергетическая политика, ИУВР.

ТҮЙІНДЕМЕ

ЖАСЫЛ СУТЕК ЖӘНЕ СУДЫҢ ҚҰНЫ: ҚАЗАҚСТАННЫҢ КАСПИЙ МАҢЫ ӨҢІРІНДЕГІ СЫН-ҚАТЕРЛЕР

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Мақалада Қазақстанның батыс аймақтарында жасыл сутек энергетикасын дамытудың келешегі су ресурстарының шектеулілігі тұрғысынан талданады. Зерттеудің өзектілігі сутектің декарбонизация стратегияларындағы негізгі элемент ретінде ғаламдық қызығушылыққа ие болуымен түсіндіріледі. Зерттеудің мақсаты — қуаң аймақтардағы сутек өндірісі мен су қамтамасыздығының өзара байланысын бағалау. Әдістемелік негізге аналитикалық шолу, салыстырмалы талдау және электролиз үдерісіндегі су тұтынуды сандық бағалау кіреді. Нәтижелер көрсеткендей, сутекті ірі көлемде өндіру айтарлықтай су ресурстарын қажет етеді және су тапшылығы бар Каспий маңы сияқты өңірлерде шектеуші факторға айналуы мүмкін. Сондай-ақ зерттеу нәтижелері тұщыландырудың баламалы су көзі ретіндегі экологиялық және экономикалық шектеулерін ашып көрсетті. Қазақстанда сутек энергетикасын орнықты дамыту су ресурстарын басқару жүйелерімен интеграцияны және келісілген саяси тәсілдерді талап етеді деген қорытынды жасалды.
Түйінді сөздер: жасыл сутек, су ресурстары, электролиз, Каспий маңы өңірі, Қазақстан, тұщыландыру, жаңартылатын энергия, су тапшылығы, энергетикалық саясат, ИУВР.

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