Energy Dialogue
Germany – Central Asia

The Role of Water for Sustainable Hydrogen Production in Kazakhstan

Part II: An initial geospatial assessment of green hydrogen hubs in Kazakhstan

dena
German Energy Agency

Legal information

Publisher:
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Acknowledgments: We would like to thank the Kazakh-German University DKU for providing the database for the development of this paper.

Last updated:
12/2023

Please cite this publication as follows:
Deutsche Energie-Agentur (Publisher) (dena, 2023) "The Role of Water for Sustainable Hydrogen Production in Kazakhstan – Part II: An initial geospatial assessment of green hydrogen hubs in Kazakhstan".

Federal Ministry for Economic Affairs and Climate Action

dena German Energy Agency

This publication was published within the framework of the German-Kazakh Energy Dialogue on behalf of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) by the Deutsche Energie-Agentur GmbH (dena).

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Key take-aways

In this study, the EU definition of renewable hydrogen is used to ensure that hydrogen is produced from renewable energy sources. In this sense, the terms 'green' and 'renewable' hydrogen are used synonymously.

Kazakhstan has abundant resources of wind and solar energy, but its water resources are scarce. As both resources are essential for sustainable renewable hydrogen production, there are certain areas that are more suitable for green hydrogen production than others. In addition to the availability of renewable electricity and water, the distance to hydrogen demand centres plays an important role.

The regions around Atyrau, Lake Balkhash, Oskemen and Pavlodar show the highest potential for establishing green hydrogen hubs (see figure below). In these areas, local water resources, the existing potential for wind and solar energy, and a future demand for hydrogen are all located in close proximity to each other. These favourable conditions allow hydrogen production close to hydrogen demand centres, linking them through the development of a local hydrogen network.

However, the areas around Aqtau, Aqtobe, Karaganda and Shymkent show the potential for the development green hydrogen production (see figure below). Here, the future centres of hydrogen demand are not located in areas with abundant water resources, making local hydrogen production less feasible. In order to deliver the required hydrogen volumes to the respective demand centres, it is therefore necessary to develop a trans-regional hydrogen network. This network can be built alongside the existing infrastructure to connect hydrogen production sites to the areas where it is needed.

In order to unlock Kazakhstan's hydrogen export potential, the development of a dedicated transport infrastructure concept is essential. This could include the construction of new infrastructure as well as conversion of existing natural gas pipelines where feasible with respect to security of gas supply.

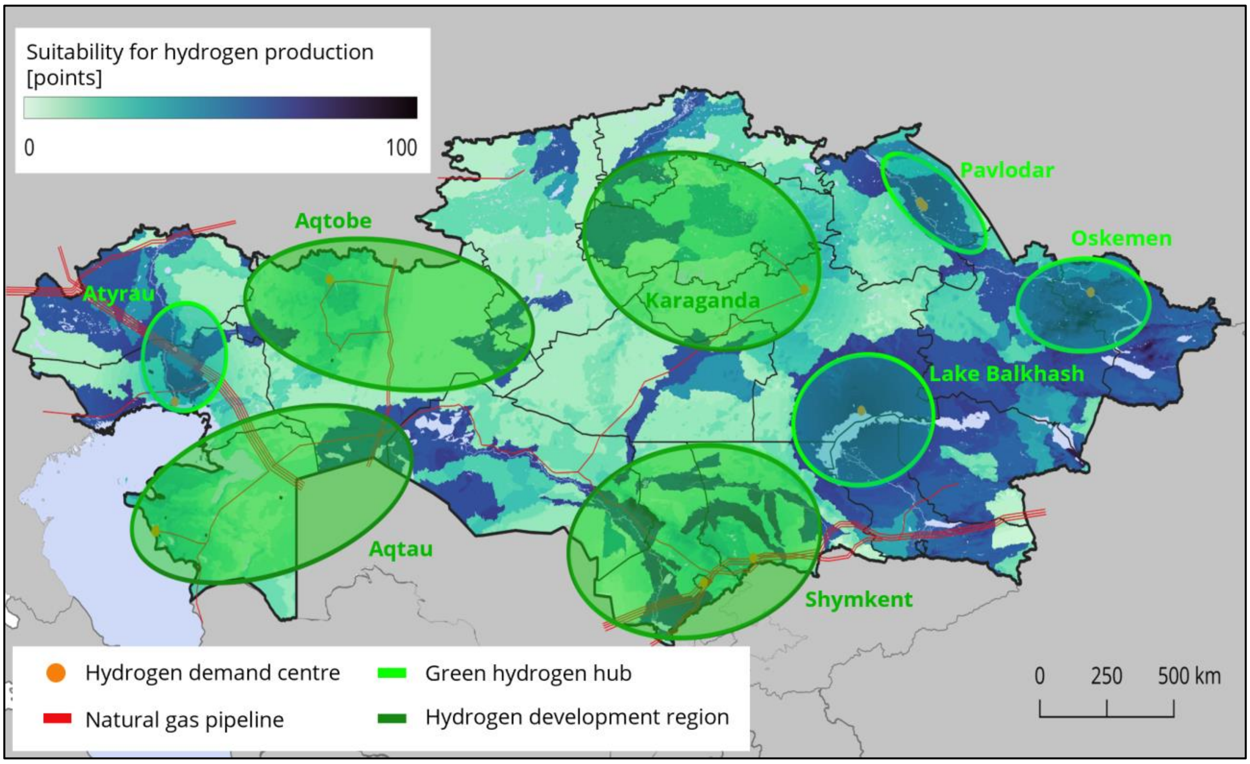

Figure: The available data for Kazakhstan indicates four green hydrogen hubs, where the green hydrogen demand and suitable production sites are in close proximity to each other, and four green hydrogen development regions, where a regional transport network would be required to connect hydrogen demand centres with suitable production sites.

1 Introduction

As a major exporter and user of fossil fuels such as coal, natural gas and crude oil, Kazakhstan's policymakers are endeavouring to set the country and its economy on a green transition pathway. Hydrogen as an energy carrier could play a vital role in the transformation of Kazakhstan's economy and society. In February 2023, President Kassym-Jomart Tokayev approved the Strategy on Achieving Carbon Neutrality by 2060 which sets ambitious net-zero carbon goals for Kazakhstan's decarbonisation. In general, the strategy recognises the considerable potential of the Central Asian country to develop renewable and alternative energies, including low carbon hydrogen, in addition to wind, solar, geothermal, nuclear and bioenergy. According to the Strategy, hydrogen is to be used primarily in applications and processes that are technically and economically difficult or impossible to electrify. Industrial applications, especially steel production, are a key focus for the utilisation of hydrogen in Kazakhstan. Kazakh production of hydrogen also offers the potential to meet Kazakhstan's ambition to position itself as an exporter of low carbon hydrogen and benefit from worldwide efforts to promote the energy transition.

The Ministry of Energy, MinEnergo, is currently formulating Kazakhstan's National Hydrogen Strategy (NHS). The goal of the NHS is to establish a framework for ramping up the national hydrogen economy until the year 2040. In line with the goals and the roadmap proposed in the NHS, initial hydrogen projects will be developed in Kazakhstan. The country has abundant resources of wind and solar energy, but its water resources are scarce. To establish this missing link, an initial analysis is needed to start developing pilot projects for the production of low carbon hydrogen in local supply and demand centres (hydrogen hubs). This paper aims to develop an information base for identifying locations for the production and use of renewable hydrogen through a multi-criteria geospatial analysis. It will thus contribute to the discussion on the development of pilot hydrogen production projects in Kazakhstan. This paper is the second part of a two-part publication on the role of water in sustainable hydrogen production in Kazakhstan. The first part explores water management for sustainable hydrogen production, for further information see dena (2023).

2 Geospatial analysis for hydrogen production sites

In the following geospatial analysis, the Quantum GIS (QGIS) application is used. QGIS is a software used for developing geographic information systems (GIS). It enables users to examine and modify geospatial data while also creating and exporting visual maps (QGIS, 2023a). Therefore, QGIS is ideal for analysing spatial problems such as the analysis of locations for the production and use of hydrogen. The following sub-sections describe in more detail the multi-criteria analysis used, the evaluation criteria and the methodology.

2.1 Multi-criteria analysis

Spatial decision-making processes often involve the consideration of multiple criteria that contribute to the complexity of the decision landscape. In this paper, a multi-criteria analysis (MCA) is used within the framework of QGIS. The integration of MCA enables a comparative evaluation of different alternatives in order to identify a preferred alternative based on its performance across different criteria. Therefore, MCA is based on a set range of attributes that selected areas should have (QGIS, 2023b). A simple additive weighting (SAW) method is used to specify the subsequent analysis. SAW assigns weights to each criterion, reflecting their relative importance in the decision-making process (Kaliszeski et al., 2016). The scores are then aggregated by adding them together, and the aggregation process is influenced by the assigned weights. The use of MCA, coupled with the application of SAW, ensures that spatial decisions are made with a comprehensive understanding of the interplay between criteria and their relative importance.

2.2 Assessment criteria

The following three sub-sections present the assessment criteria and the data gathered for conducting the MCA. The focus of the analysis lies on the spatial availability of natural resources such as wind, solar energy and water. Centres of first-mover applications such as refineries, ammonia and steel production are also taken into account for the analysis.

A potential hydrogen production site can receive a total of 100 points. The criteria are listed in table 1 and have been weighted in an evaluation process. The availability of water is particularly critical in an arid country such as Kazakhstan, and therefore it is weighted with 50 points. This is followed by the availability of renewable energy sources with 35 points. Proximity to potential demand centres is also important for decentralised pilot projects close to hydrogen consumers.

Table 1: Weighting of the identified criteria for hydrogen production pilot projects

Criterion	Points
Available water resources	max. 50 points
Renewable energy potential (wind, PV)	max. 35 points
Proximity to hydrogen demand centres	max. 15 points

2.2.1 Solar and wind energy potential

The availability of abundant renewable energy is a critical prerequisite for the generation of renewable hydrogen through water electrolysis. Kazakhstan's vast territory, geographical profile and climatic conditions offer the potential for abundant renewable energy production.

The country's government aims to take advantage of this potential and has drafted plans to increase the use of renewable energy. Increasing from approx. 4.5% at the end of 2022, 12.5% of Kazakhstan's electricity will come from renewable sources by 2029 (QazaqGreen, 2023a). The government plans to install 6.5 GW of renewable energy generation capacity by 2035 (QazaqGreen, 2023b). A "Draft Concept for Development of the Fuel and Energy Complex and the Electricity Sector" lays out the deployment pathway to achieve this increase. In 2022, 12 projects with a total capacity of 385 MW were realised. A further ten projects (or 276 MW) are planned for 2023 (QazaqGreen, 2023c) and, along with another 41 projects, will total 757 MW by 2025.

In order to identify promising sites for hydrogen production, this paper assesses the renewable energy potential of the two most relevant technologies in Kazakhstan: solar photovoltaic (PV) and onshore wind energy. This is based on publicly available databases of specific photovoltaic power output (kWh/kWp) and wind power density (W/m^2) at a hub height of 100 metres (World Bank Group, 2023a; World Bank Group, 2023b).

A potential production site can theoretically achieve a maximum of 35 points out of a total 100 points. Due to its more homogenous production profile and therefore better suitability for hydrogen generation, wind resource availability is weighted with 70% of these points (25 points), leaving 30% for solar PV (10 points). Table 2 shows the thresholds applied to classify sites according to their renewable energy potential, and converts suitability into points.

Table 2: Classification scheme for renewable energy potential applied as part of this analysis

Renewable energy potential	max. 35 points	
Onshore wind	25 points	Power density ≥ 1250 W/m^2
	20 points	Power density ≥ 1000 W/m^2
	15 points	Power density ≥ 750 W/m^2
	10 points	Power density ≥ 500 W/m^2
	5 points	Power density ≥ 250 W/m^2
Solar PV	10 points	Power output ≥ 4.5 kWh/kWp
	8 points	Power output ≥ 4.0 kWh/kWp
	6 points	Power output ≥ 3.5 kWh/kWp
	4 points	Power output ≥ 3.0 kWh/kWp
	2 points	Power output ≥ 2.5 kWh/kWp

2.2.2 Water resources

In addition to the electricity produced from renewable sources such as wind and solar energy, water is an integral component in the production of low carbon hydrogen. Water resources, mostly surface water, are extremely unevenly distributed across the country and subject to seasonal fluctuations. Furthermore, Kazakhstan's water resources are also highly dependent on water inflows from neighbouring countries. About 54% of the surface water inflow has its origin in Kazakhstan's neighbouring states, namely China, Uzbekistan, Kyrgyzstan and Russia (Sarsenbekov et al., 2016).

In the coming years, climate change is expected to exacerbate the water situation in Kazakhstan. Temperature shifts as well as precipitation shifts have already been observed, and have resulted in desertification and degradation of croplands and pastures (Droogers et al., 2018). Estimates assume that 66% of the irrigated land in Kazakhstan is already subject to some form of degradation (UNDP, 2022). Out of Kazakhstan's eight major water basins, four are most vulnerable to climate change. By the end of this century, it is projected that the sea level in the Caspian Sea will fall by 9 to 18 metres (Kaleji, 2023). The decrease in the sea level is caused by a substantial increase in lake evaporation and a decrease in precipitation or river discharge. Given the trend of population and economic growth, by 2040, the water deficit in Kazakhstan could reach 12 to 15 billion cubic metres (Sanchez, 2023).

In this paper, the state of the water resources is identified by the level of water stress in a dedicated area. Water stress is defined as the ratio of demand to supply. Therefore, the Aqueduct 3.0 dataset, a water risk framework provided by the World Resource Institute (WRI) is used for the analysis (Hofste et al., 2023). The dataset consists of 13 baseline water risk indicators, including quantity, quality and reputational concerns. For this analysis, the indicator baseline water stress is taken as a measure for the availability of water in a certain location. In the WRI's Aqueduct framework, baseline water stress is calculated based on data about water withdrawal, available water and groundwater data in a global hydrological model. The data sets are available for each month between January 1960 and December 2014. Aqueduct defines water use through two metrics: gross demand and net consumption. Here, gross demand is the maximum potential volume of water required to meet sectoral demands, and net consumption is the portion of demand that is lost in use, for example, through evaporation or incorporation into a product.

Out of the maximum 100 points that a potential site can achieve, 50 points are dedicated to the availability of water resources. The exact distribution of points is shown in table 3.

Table 3: Classification scheme for the available water resources in Kazakhstan

Available water resources	max. 50 points	
low water stress	50 points	water stress under 10%
low-medium water stress	30 points	water stress between 10 to 20%
medium-high water stress	10 points	water stress between 20 to 40%
high water stress	0 points	water stress between 40 to 80%
extremely high water stress	0 points	water stress above 80%

2.2.3 Hydrogen demand centres

According to the Strategy on Achieving Carbon Neutrality by 2060, hydrogen should primarily be used in applications and processes that are difficult or impossible to electrify. Therefore, in this analysis, the assumption is made that low carbon hydrogen will be used first in emission-intensive and hard-to-abate processes and that it will be produced physically close to the offtake. In Kazakhstan, this applies in particular to the production of steel, the chemical industry and refinery processes (Zholdayakova et al., 2022; dena and AHK Central Asia, 2022).

Most processing factories and metallurgical plants in Kazakhstan are concentrated in the north and north-east, such as in the cities of Semey, Astana, Petropavlovsk and Aqtobe. In South and Central Kazakhstan, the most important industrial centres are Shymkent, Almaty and Taraz, with the focus on the chemical, light and food industries as well as metallurgy and machine building. According to KazEnergy's national report, Kazakhstan's three main refineries – Atyrau, Pavlodar and Shymkent – process about 15 million tonnes of the country's total volume of oil. They account for over 90% of the country's overall refining throughput, with the remainder refined in 34 smaller refineries. Individually, they produce small quantities of low-value products or semi-finished goods, but they also play an important role in supplying the market with fuel, which is mainly used in agriculture. Due to the existing infrastructure and the huge decarbonisation potential of these sectors by means of low carbon hydrogen, the three major refineries, the largest industrial plants in metallurgical, steel and the chemical sector, were considered as hydrogen demand centres for the purposes of this analysis. In total, 12 potential demand sites, five metallurgical plants, four refineries and three chemical plants were identified.

The analysis focuses on the identification of decentralised production and use of hydrogen. Proximity to demand centres is therefore a criterion for the decentralisation of a potential low carbon hydrogen production site to a potential demand site. Out of a maximum of 100 points, 15 points are allocated to proximity to demand centres. Table 4 shows the exact distribution of points.

Table 4: Classification scheme for proximity to the identified hydrogen demand centres

Proximity to demand centres	max. 15 points	
Distance between hydrogen production and usage sites	15.0 points	distance ≤ 50 km
	13.5 points	distance ≤ 75 km
	12.0 points	distance ≤ 100 km
	10.5 points	distance ≤ 125 km
	9.0 points	distance ≤ 150 km
	7.5 points	distance ≤ 175 km
	6.0 points	distance ≤ 200 km
	4.5 points	distance ≤ 225 km
	3.0 points	distance ≤ 250 km
	1.5 points	distance ≤ 275 km
	0.0 points	distance over 275 km

2.3 Methodology

This section describes the detailed approach taken by the multi-criteria analysis. The analysis of suitable sites for pilot projects for hydrogen production in Kazakhstan involves several steps, which are explained below.

The initial requirement involves converting available vector data into raster maps. This includes the transformation of baseline water stress data and demand centres, presented as data points with latitude and longitude. In addition, wind and solar potential data are readily available as raster maps from the data source. Subsequently, a proximity map of the demand centre is generated, assigning points based on distance to the closest demand centre. Finally, scores are attributed to the data, as detailed in section 2.2, using the tool raster calculator in QGIS. A maximum of 100 points can be assigned, 50 points for water stress, 35 points for wind and solar potential and 15 points for potential demand centres.

In the initial phase of the analysis, the baseline water stress layer and its corresponding points overlay the renewable potential map, consisting of solar power output and wind power density, with the weighting described in section 2.2.1. The final step involves overlaying the demand centres map, resulting in a comprehensive map which highlights suitable production sites for low carbon hydrogen pilot projects in Kazakhstan.

The focus of the analysis is exclusively on areas in mainland Kazakhstan. The natural gas network was added to the final map to provide a visual representation of the potential connections. However, due to a lack of data about pipeline quality and the potential for conversion to hydrogen pipelines, proximity to pipelines did not influence the overall suitability score.

3 Results and discussion

The analysis of baseline water stress in Kazakhstan reveals distinct patterns. Regions in close proximity to the Aral Sea, Lake Balkhash, Lake Zaysan, and the northern and eastern coasts of the Caspian Sea show particularly low water stress. In addition, areas surrounding various rivers, including the Ili, Syr Darya, Ural, Esil, and Irtysh, display either low or no water stress, further increasing their potential suitability for hydrogen production. The border areas of Almaty oblast, south-east of Karaganda oblast, and Eastern Kazakhstan show a low water risk according to the data. Consequently, these areas have the highest potential regarding water availability for hydrogen production. Conversely, certain huge areas in Kazakhstan, exemplified by the eastern part of Ulytau, Mangystau oblast as well as vast areas of Aqtobe oblast, suffer from high water stress. This predicament indicates a diminished potential for setting up hydrogen production sites in these regions (see figure 1).

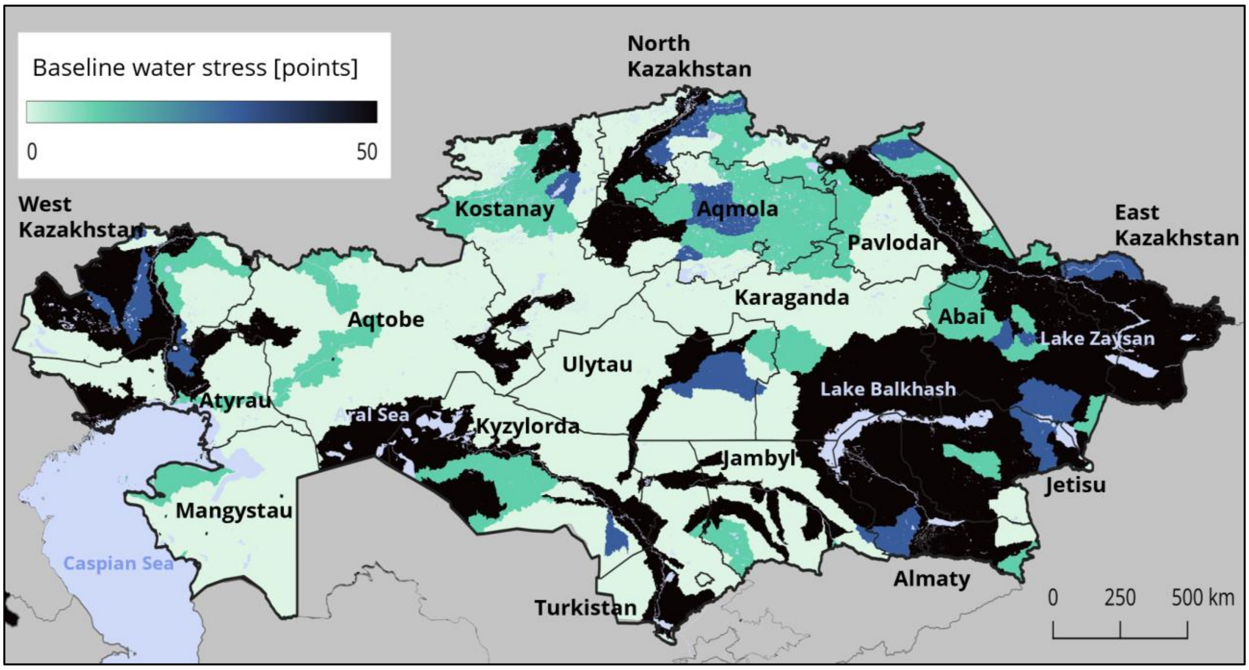

Figure 1: Existing water stress excludes large areas in the central regions of Kazakhstan from being suitable for green hydrogen production. Own illustration based on data from WRI Aqueduct, 2019 & GeoBoundaries, 2023.

The inclusion of renewable energy potential for onshore wind and solar PV in the assessment strengthens the viability of certain regions, while others lag behind due to lower renewable energy potential. In particular, areas such as Kyzylorda have high PV potential, as do Turkistan, Jambyl, the northern part of Almaty, the southern part of Karaganda and the northern part of Jetisu oblast. This shows that the southern part of Kazakhstan has significant renewable energy potential. However, these regions also suffer from water stress, which partially reduces their overall score. Mangystau oblast has the highest renewable energy potential, particularly in terms of wind power density. However, the region's high water stress reduces the overall suitability for hydrogen production. Nevertheless, desalinating water from the Caspian Sea emerges as a viable option to alleviate water scarcity in this area, thereby enhancing the availability of water for hydrogen production. This analysis step highlights a clear relationship between renewable potential, water stress and evolving suitability of different regions for hydrogen production sites (see figure 2).

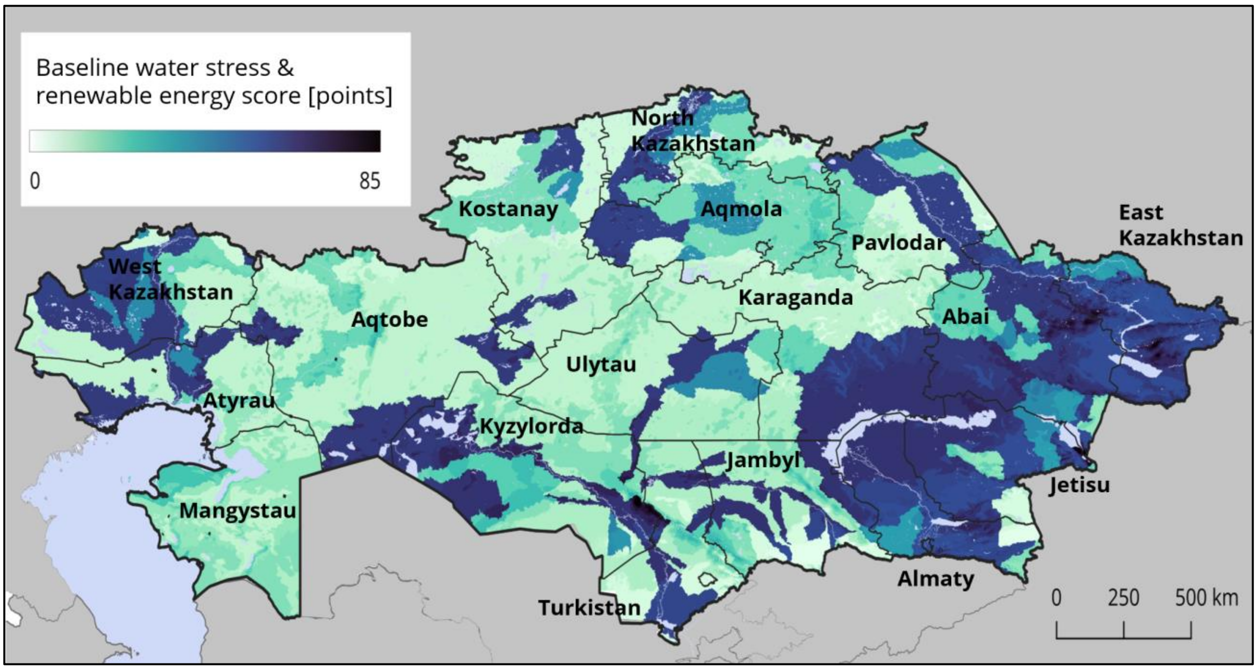

Figure 2: The eastern parts of Kazakhstan and local areas in other parts of the country have the most favorable conditions for green hydrogen production when taking into account both existing water resources and renewable energy (onshore wind, solar PV) potential. Own illustration based on data from WRI Aqueduct (2019); GeoBoundaries (2023); World Bank Group (2023a) and World Bank Group (2023b).

The inclusion of hydrogen demand centres highlights significant additional potential in the southern and eastern regions of Kazakhstan. Not only do they underline the already high potential of eastern Kazakhstan and the region around Lake Balkhash, but also extend to areas around Oskemen, Atyrau, and Pavlodar. Conversely, the central part of Kazakhstan, characterised by water stress, lower renewable energy potential and the absence of industrial demand centres, is one of the least suitable areas for hydrogen production. This observation underlines the importance of water resources, renewable energy potential and hydrogen demand in determining the feasibility of hydrogen projects. It is worth noting that only 5 out of 12 demand centres centres are located in areas with favourable conditions to produce green hydrogen, emphasising the possibility to develop local hydrogen production and use (see figure 3).

In this study, the criteria for a green hydrogen hub are the availability of water, existing potential for wind and solar energy, and a local demand for hydrogen. With the aim of identifying potential areas for decentralised hydrogen production and use in Kazakhstan, it is noticeable that favourable conditions for renewable hydrogen hubs exist near demand centres in the Lake Balkhash, Oskemen, Pavlodar and Atyrau areas (see figure 4 in blue). Near the demand centres in Aqtau, Aqtobe, Shymkent, and the Karaganda area, the demand for hydrogen is not inherently aligned with abundant water resources. Therefore, makes hydrogen production less feasible in these areas. In order to supply these areas with green hydrogen, it would therefore be necessary to develop a regional hydrogen transport network. This regional hydrogen transport network would effectively connect existing demand centres with production sites in regional proximity. This fact indicates the potential for green hydrogen development regions in the area of Aqtau, Aqtobe, Shymkent and Karaganda (see figure 4 in green).

The inclusion of the gas network in figure 4 shows a well-developed infrastructure in the southern and western regions of Kazakhstan, while the central, northern and eastern parts of Kazakhstan are not connected. This is due to the fact that most of the gas produced in Kazakhstan is associated gas, a by-product of oil production. Over 75% of Kazakhstan's gas production comes from the Caspian Basin where the Karachaganak, Kashagan and Tengiz projects are operated[1]. Keeping Kazakhstan's ambition to position itself as an exporter of low carbon hydrogen in mind, it will become vital for the country to establish a dedicated hydrogen transport infrastructure. This could include the construction of new infrastructure or the conversion of existing natural gas pipelines where feasible.

[1] https://economy.kz/ru/Mnenija/id=139

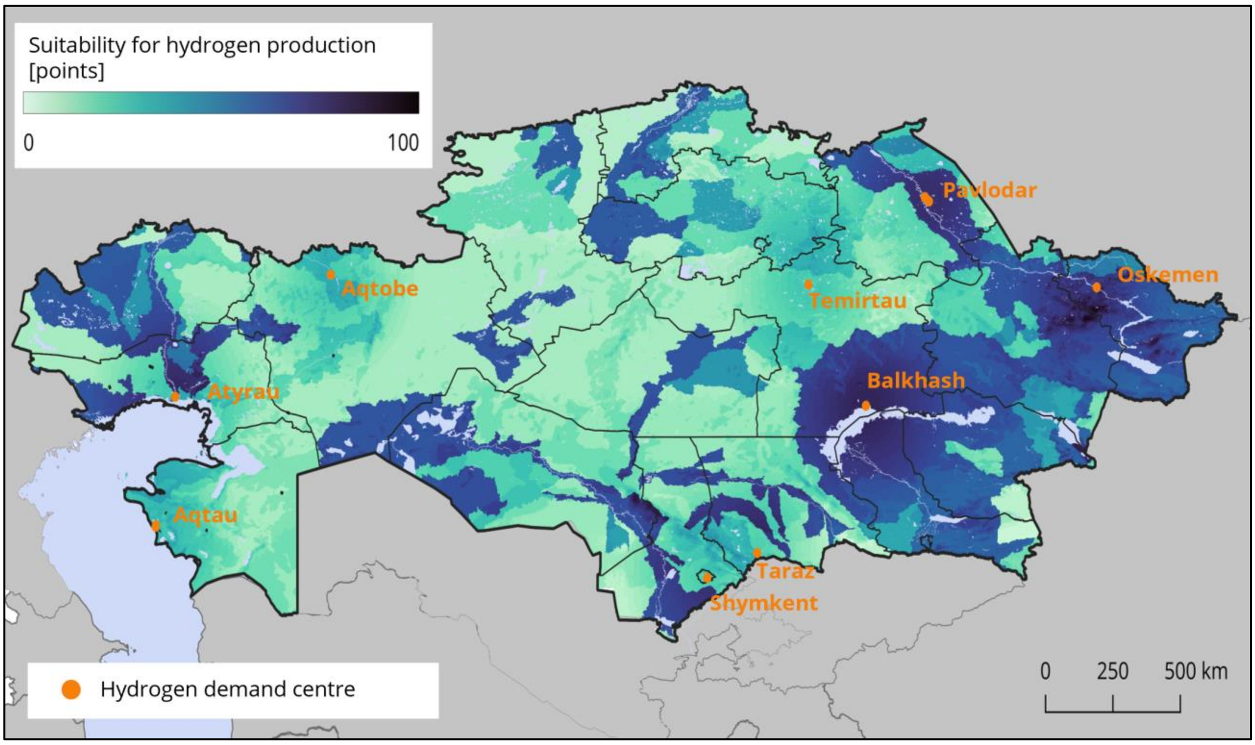

Figure 3: Only 5 out of 12 hydrogen demand centres are located in areas with favourable green hydrogen production conditions. Own illustration based on data from WRI Aqueduct (2019); GeoBoundaries (2023); The World Bank Group (2023a); The World Bank Group (2023b).

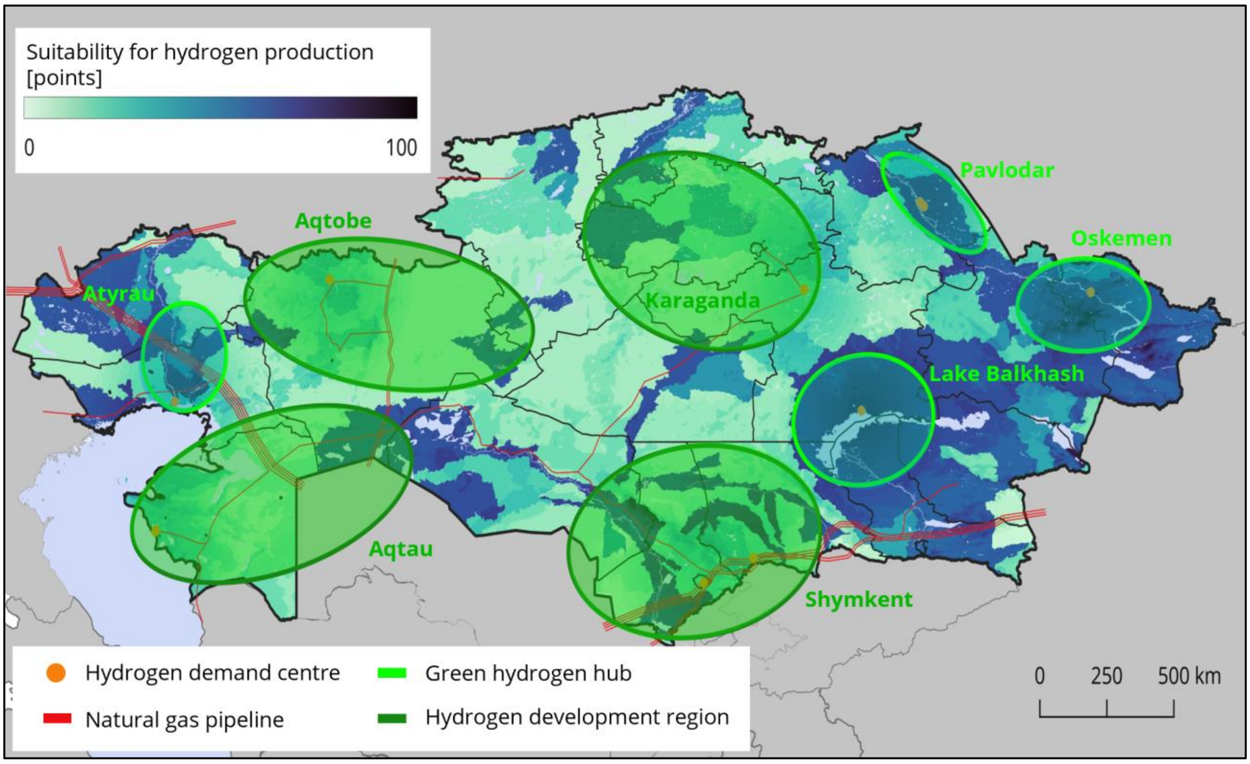

Figure 4: The available data for Kazakhstan indicates four green hydrogen hubs, where the green hydrogen demand and suitable production sites are in close proximity to each other, and four green hydrogen development regions, where a regional transport network would be required to connect hydrogen demand centres with suitable production sites. Own illustration based on data from WRI Aqueduct (2019); GeoBoundaries (2023); The World Bank Group (2023a); The World Bank Group (2023b); GIZ (2023).

4 Limitations

While the analysis presented provides insights into potential green hydrogen hubs in Kazakhstan, it is important to acknowledge certain limitations inherent in the methodology and data used. These limitations warrant caution in drawing definitive conclusions, and underscore the need for further research and refinement. Addressing these limitations through more detailed site assessments, nuanced analysis of the future hydrogen demand, and incorporation of current data about environmental factors will improve the accuracy and reliability of future hydrogen production planning in Kazakhstan.

It is vital to recognise that the approach used to identify suitable sites for green hydrogen hubs serves merely as an initial assessment. The analysis considers factors such as water resources, wind and solar potential, and provides a broad overview of promising sites. However, a more in-depth assessment is required to determine the true techno-economic potential of setting up wind or photovoltaic farms at these sites. This would require a comprehensive analysis that takes into account additional factors, including topography, soil composition, infrastructure accessibility and environmental impact assessments. In addition, the assessment of potential hydrogen demand centres is a complex task that requires a more nuanced quantitative analysis. The current approach provides a preliminary indication of areas where there is a future hydrogen demand, but lacks the granularity required to accurately estimate the amount of hydrogen needed. Further studies should look into the specific needs of each demand centre, taking into account industrial processes, transportation needs, and other sector-specific factors in order to develop a more accurate understanding of the demand. Furthermore, the data used to assess water stress in certain regions originates from the period from 1960 to 2014. Given the dynamic nature of environmental conditions, relying on past data can lead to inaccuracies in identifying future water stress levels. A more robust assessment using more recent or maybe even predicted data and taking climate change effects into account is essential for providing a realistic picture of the current water stress scenario. This will ensure that any strategies proposed to address water scarcity, such as desalination projects, are in line with current conditions.

5 Conclusions

In conclusion, the multi-criteria geospatial analysis of hydrogen production and demand in Kazakhstan has revealed distinct patterns and opportunities across various regions. A convergence of favourable conditions for green hydrogen production provides the opportunity to establish green hydrogen hubs. These conditions are the availability of water, existing potential for wind and solar energy and a local demand for hydrogen. For Kazakhstan, this indicates the potential to establish four green hydrogen hubs in the areas of Lake Balkhash, Oskemen, Atyrau, and Pavlodar. This would provide the basis for decentralised hydrogen production in Kazakhstan. In addition, the analysis shows the potential for four hydrogen development regions in Aqtau, Aqtobe, Shymkent, and Karaganda. Here, the future demand for hydrogen is not inherently aligned with abundant water resources. This mismatch necessitates the development of a regional hydrogen transport network to effectively link hydrogen demand with production sites.

One of the most significant challenges identified is water stress in the windy areas of Ulytau, Jambyl and Mangystau oblast, which poses a hindrance to using the full potential of hydrogen production. For the Mangystau oblast area, desalinating water from the Caspian Sea emerges as a viable solution to alleviate water scarcity in this area, thereby enhancing the availability of water for hydrogen production.

To fully capitalise on Kazakhstan's hydrogen export potential, the establishment of a dedicated transport infrastructure concept will be indispensable. This projected infrastructure could involve the construction of new transport corridors or the conversion of existing natural gas pipelines where feasible, thus demonstrating a pragmatic and efficient utilisation of existing resources. This strategic development would facilitate the seamless transportation of hydrogen from production hubs to export terminals, contributing to the country's ambition to position itself as a player in the global hydrogen market.

Despite the promising prospects outlined in the analysis, it is evident that further assessment is imperative in order to accurately identify potential pilot projects. A more in-depth techno-economic understanding of the hydrogen hubs identified is crucial for assessing the true feasibility of proposed projects. Conducting an environmental impact assessment is vital to avoid or minimise conflicts with other water users such as water for irrigation. In addition, the assessment of potential hydrogen demand centres is a complex and requires a more nuanced quantitative analysis. This calls for continued research efforts and collaboration between all stakeholders in order to overcome any unforeseen challenges and ensure the successful implementation of hydrogen initiatives in Kazakhstan.

Sources

Deutsche Energie-Agentur (dena) (Publisher) (2023) 'The Role of Water for Sustainable Hydrogen Production in Kazakhstan – Part I: Water management for the production of sustainable hydrogen'.

Deutsche Energie-Agentur (dena) and Delegation German Economy in Central Asia (AHK Central Asia) (Publishers) (2022) 'Hydrogen in Kazakhstan: potential development areas', Available at: https://filehub.admiralcloud.com/v5/deliverFile/64898cbb-f2bb-4b7a-9c4c-74bfc9eb33a8 (Accessed: 29 December 2023).

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (2023) 'Green Hydrogen Transport Scenarios: From Kazakhstan to Europe', Available at: https://www.h2diplo.de/fileadmin/user_upload/Green_Hydrogen_Transport_Scenarios_from_Kazakhstan_to_Europe__Final_report.pdf (Accessed: 30 December 2023).

Droogers, P.; Murari L. (2018): 'Kazakhstan Irrigation Rehabilitation Sector Project: Climate Risk and Vulnerability Assessment Report', Available at: https://www.adb.org/sites/default/files/linked-documents/50387-001-sd-05.pdf (Accessed: 12 October 2023).

Economic and Social Commission for Asia and the Pacific (2014): 'KAZAKHSTAN: Concept for the Development of the Fuel and Energy Sector until 2030' Asia Pacific Energy Portal, Available at: Concept for the Development of the Fuel and Energy Sector until 2030 | ESCAP Policy Documents Managment (asiapacificenergy.org) (Accessed: 30 May 2023).

GeoBoundaries (2023): 'Simplified Country Files', Available at: https://docs.google.com/document/d/1K-jCivgY3fPNZUzXWMSDmyYGon1fSh4bqAEcTItPfjI/edit (Accessed: 7 September 2023).

Hofste, R.W et al. (2023): Aqueduct 3.0: Updated Decision-relevant Global Water Risk Indicators, World Resource Institute, Available at: https://files.wri.org/d8/s3fs-public/aqueduct-30-updated-decision-relevant-global-water-risk-indicators_1.pdf (Accessed: 30 October 2023).

Kaliszeski, I., Podkoppaev, D. (2016): 'Simple additive weighting - A metamodel for multiple criteria decision analysis methods', Expert Systems with Applications, 54(2016), pp 155-161. doi: https://doi.org/10.1016/j.eswa.2016.01.042 (Accessed: 01 December 2023).

Kaleji, V. (2023): 'Decreasing Water Levels in the Caspian Sea: Causes and Implications', The Central Asia-Caucasus ANALYST - Analytical Articles, Available at: https://www.cacianalyst.org/publications/analytical-articles/item/13769-decreasing-water-levels-in-the-caspian-sea-causes-and-implications.html#:~:text=The%20Caspian%20Sea%20level%20is,results%20would%20clearly%20be%20disastrous (Accessed: 23 October 2023).

QazaqGreen (2023a): 'Kazakhstan to increase the share of electricity production from renewables in total generation to 12.5% by 2029', 7th February. Available at: https://qazaqgreen.com/en/news/kazakhstan/976/ (Accessed: 25 May 2023).

QazaqGreen (2023b): 'Kazakhstan to create the most attractive conditions for investors in renewable energy projects', 17th January, Available at: https://qazaqgreen.com/en/news/kazakhstan/918/ (Accessed: 25 May 2023).

QazaqGreen (2023c): 'Kazakhstan to commission 10 RES projects in 2023 with a capacity of 276 MW - Energy Ministry', 1st February, Available at: https://qazaqgreen.com/en/news/kazakhstan/962/ (Accessed 25 May 2023).

QazaqGreen (2023d): 'Kazakhstan to launch 41 renewable energy projects by 2025', 17th February, Available at: https://qazaqgreen.com/en/news/kazakhstan/1008/ (Accessed: 25 May 2023).

QGIS (2023a): 'QGIS - The Leading Open Soruces Desktop GIS', Available at: https://qgis.org/en/site/about/index.html (Accessed: 24 November 2023).

QGIS (2023b): 'Multi Criteria Overlay Analysis (QGIS3)', Available at: https://www.qgistutorials.com/en/docs/3/multi_criteria_overlay.html (Accessed: 09 October 2023).

Sanchez, W.A. (2023): 'Kazakhstan Aims to Protect the Blue while Going Green', Geopolitical Monitor - Situation Reports, Available at: https://www.geopoliticalmonitor.com/kazakhstan-aims-to-protect-the-blue-while-going-green/ (Accessed: 24 October 2023).

Sarsenbekov, T.T.; Ahmetov, S.K. (2016): ‘Republic of Kazakhstan - Country Report’, Available at: https://www.gwp.org/globalassets/global/gwp-cacena_files/en/pdf/kazakhstan.pdf (Accessed: 10 July 2023).

Syzdykov, B. (2023): ‘Текущее состояние газовой отрасли в Казахстане’, Economic Research Institute - Chairman’s Blog, 26th May. Available at: https://economy.kz/ru/Mnenija/id=139 (Accessed: 15 September 2023).

United Nations Development Programme (2022): ‘Landscape planning – a guardianship for safeguarding ecosystem’, 5th July, Available at: https://www.undp.org/kazakhstan/stories/landscape-planning-guardianship-safeguarding-ecosystem#:~:text=Today%2C%20degraded%20lands%20occupy%20an,to%20wind%20and%20water%20erosion (Accessed: 16 October 2023).

World Bank Group (2023): ‘Global Solar Atlas’. Available at: https://globalsolaratlas.info/map (Accessed: 15 December 2023).

World Bank Group (2023a): ‘Global Wind Atlas’. Available at: https://globalwindatlas.info/en (Accessed: 15 December 2023).

World Resource Institute (2019): ‘Aqueduct Global Maps 3.0 - Data’, Available at: https://wri-projects.s3.amazonaws.com/Aqueduct30/finalData/Y2019M07D12_Aqueduct30_V01.zip (Accessed: 13 September 2023).

Zholdayakova, Saul; Abuov, Yerdaulet; Zhakupov, Daulet, Suleimenova, Botakoz; Kim, Alisa (2022): ‘Toward Hydrogen Economy in Kazakhstan’, ADBI Working Paper Series, No. 1344, Available at: https://www.adb.org/sites/default/files/publication/836516/adbi-wp1344.pdf (Accessed: 15 July 2023).

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List of abbreviations

GIS	Geographic information system
MCA	Multi-criteria analysis
NHS	National Hydrogen Strategy
PV	Photovoltaic
QGIS	Quantum GIS
SAW	Simple additive weighting
WRI	World Resource Institute