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Hydrogen energy in Kazakhstan: prospects for development and potential

Abstract: Kazakhstan possesses significant natural resources, including coal, oil, natural gas, and uranium, and also has substantial potential for utilizing renewable energy sources such as wind, solar, hydropower, and biomass. However, the country currently relies heavily on fossil fuels for electricity generation. Coal-fired power plants account for 75% of the total electricity production, raising concerns about greenhouse gas emissions and their detrimental impact on human health and the environment. In December 2020, at the Climate Ambition Summit, the President of Kazakhstan announced a new goal for the country to achieve carbon neutrality by 2060. To attain this objective, the government faces the ambitious task of developing a strategy for the development of hydrogen energy in Kazakhstan.

This review extensively discusses Kazakhstan's main energy resources, the potential for low-carbon and green hydrogen production, existing and prospective pilot projects in the field of hydrogen, as well as the challenges and barriers hindering the development of hydrogen energy in Kazakhstan. Authors consider existing research, national reports, energy strategies, and plans to discuss the

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prospects for hydrogen energy development in Kazakhstan. The transition to hydrogen energy in Kazakhstan requires the development of a comprehensive roadmap that takes into account various aspects such as production, infrastructure development, policy support, and international cooperation. Currently, the country lacks a roadmap for hydrogen energy development that considers these crucial aspects. Therefore, as a result of this review, we have developed a new roadmap for hydrogen production by 2040 in Kazakhstan, incorporating various technologies. Authors believe this roadmap will be valuable information for the government to develop a national strategy for the active development of hydrogen energy in Kazakhstan.

Keywords: hydrogen energy, Kazakhstan, renewable energy sources, green hydrogen, carbon neutrality

Introduction

The utilization of hydrogen energy is poised to play a pivotal role in the imminent technological revolution anticipated within the next few decades (Molenda 2008). As per research findings from Bloomberg NEF, hydrogen is projected to satisfy roughly 24% of the global energy demand by 2050. A substantial investment of around 11 trillion dollars is expected to be allocated to this sector, with hydrogen fuel sales reaching an impressive annual sum of 700 billion dollars (Molenda 2008; Falcone et al. 2021). It is important to highlight that leading industrial nations are already actively engaged in the competition to advance alternative energy sources (Hosseini 2022).

Since the early 2000s, numerous nations, including Germany, the United Kingdom, India, China, the United States, Japan, and South Korea, have been actively implementing comprehensive programs to advance hydrogen energy. These countries have formulated long-term national strategies between 2018 and 2020 to attain specific objectives (Hosseini 2022; Chanchetti et al. 2020). Examples of this are that Japan endorsed its Basic Hydrogen Energy Strategy in 2017, South Korea devised a new roadmap for hydrogen energy in 2018, China published the White Paper on hydrogen energy in 2019, Australia implemented a national strategy, and the European Union adopted the European Hydrogen Strategy for 2050 in 2020 (Khomamatovich et al. 2022; Solovyev et al. 2019).

In the twenty-first century, hydrogen has emerged as a significant energy carrier due to its ability to combine the benefits of conventional hydrocarbon fuels with the demands of a sustainable economy (Solovyev et al. 2019). A key advantage of hydrogen is its carbon-neutral nature as it generates only water when used as fuel, thereby aligning perfectly with the principles of a "green" economy (Opakhai et al. 2023). Moreover, hydrogen presents various opportunities, including the conversion of electricity into fuel, efficient storage and convenient transportation, making it an indispensable alternative to traditional oil and gas sources (Tomczyk 2009).

Hydrogen exhibits its versatility by being compatible with existing internal combustion engines designed for gasoline and natural gas, as well as fuel cells that convert chemical energy into electrical energy (Aydin et al. 2018; Tarhan et al. 2021). Another notable advantage of hydrogen is its high specific heat of combustion, surpassing that of gasoline by 3–3.5 times, which renders it economically favorable even at current market prices ranging from \$1.5 to \$5 per kilogram (Tarhan et al. 2021). As of the start of 2021, worldwide investments in hydrogen energy had already surpassed \$90 billion (Tomczyk 2009).

Drawing from the national strategies adopted by the aforementioned countries, four primary directions can be discerned for the advancement of hydrogen energy (Kovač et al. 2021; Turoń 2020):

1. Encouraging the adoption of hydrogen-powered vehicles, particularly in the automotive industry, with the aim of reducing carbon dioxide emissions and implementing environmentally friendly technologies within the transportation system (Turoń 2020).

2. Expanding hydrogen production capabilities to meet the increasing demand for this fuel. This entails the development and implementation of efficient hydrogen production technologies from diverse sources, such as electrolysis, natural gas reforming, and the utilization of renewable energy sources (Tańczyk et al. 2009).

3. Enhancing hydrogen logistics, encompassing the establishment of efficient distribution, storage, and transportation systems for hydrogen. This is crucial to ensure the availability and reliability of hydrogen supply across various regions and economic sectors (Lam et al. 2019).

4. Developing and deploying hydrogen power stations that utilize hydrogen-based fuel cells to generate electricity. Such stations can play a pivotal role in providing stable and environmentally clean energy sources for diverse sectors, including the energy industry, manufacturing, and residential domains (Ceran 2018).

At present, Japanese companies like Toyota and Honda are at the forefront of hydrogen fuel cell vehicle production. Toyota's Mirai model has already surpassed 12,000 vehicles globally, including 7,000 vehicles in the United States, while Honda's FCX Clarity model has over 38,000 vehicles in operation. Projections suggest that by 2030, Japan will have approximately 800,000 units of hydrogen-powered vehicles, indicating a gradual yet substantial rise in interest and the adoption of this technology within the automotive industry (Albatayneh et al. 2023).

The International Energy Agency (IEA) reports that global hydrogen production reached 74 million metric tons in 2018, primarily catering to the needs of the petrochemical and metallurgical sectors. Projections for the growth of hydrogen energy and transportation indicate a substantial surge in demand, reaching 30–35 million metric tons of clean hydrogen by 2030 (Karpiński 2012). This translates to annual expenditures of approximately \$600–700 billion, based on current prices. Notably, this expenditure volume is roughly equivalent to one-third of the global oil market, which is valued at \$1.9 trillion (Thaysen et al. 2021). Countries possessing hydrogen production capabilities, such as Kazakhstan, have the potential to leverage hydrogen energy as a significant catalyst for economic development (Tleubergenova et al. 2023).

The development of green hydrogen carries significant importance for Kazakhstan for several reasons. Firstly, the country's close ties with the European Union (EU) as a crucial trading partner make the EU Green Deal particularly relevant. The implementation of elevated tariffs on non-green products by the EU can have substantial implications for Kazakhstan's economy in the medium and long term (KAZAKH INVEST 2022).

In addition to the above point, Kazakhstan has entered into a Memorandum of Understanding with the European Bank for Reconstruction and Development (EBRD) to establish strategic cooperation aimed at attaining carbon neutrality in the country's energy sector by 2060 (Ministry of Energy of the Republic of Kazakhstan 2022).

To achieve carbon neutrality, Kazakhstan has embraced a political strategy centered around "deep decarbonization" which involves leveraging existing technologies, primarily in the energy sector, to significantly minimize CO_2 emissions. The objective is to reduce emissions by approximately 78% in comparison to the 1990 level (Capital 2023).

In this review article, the possibilities of developing hydrogen energy in Kazakhstan are thoroughly discussed. With its abundant natural resources, Kazakhstan aims to utilize its potential in the field of hydrogen energy and transition towards a sustainable energy future. The review explores existing prospects for green hydrogen production from renewable energy sources, political frameworks, infrastructure development in the hydrogen sector, and identifies key challenges and opportunities. It also discusses potential benefits of low-carbon hydrogen production, logistical possibilities and limitations for hydrogen export projects, as well as energy diversification, carbon emissions reduction, economic growth, and international cooperation. The conclusion of the review article outlines the prospects of hydrogen energy in Kazakhstan and proposes a new roadmap for successful implementation in this direction.

1. The energy landscape of Kazakhstan

Kazakhstan's energy landscape is predominantly influenced by its abundant natural resources, particularly hydrocarbons. However, the country is actively working towards diversifying its energy system by concurrently developing traditional and renewable energy sources. This strategic approach aims to enhance energy security, bolster economic efficiency, and mitigate adverse environmental effects (Adilbektegi et al. 2019). This section offers an overview of the essential elements that constitute Kazakhstan's energy landscape, encompassing an examination of its energy resources, infrastructure, and future prospects.

1.1. Energy resources of Kazakhstan

Kazakhstan, the largest landlocked country in the world, encompasses a vast territory of 2,724,900 square kilometers and is positioned without direct access to the sea. It shares borders with China, Kyrgyzstan, the Russian Federation, Turkmenistan, and Uzbekistan, and is also in proximity to the Caspian Sea (Arslan 2014; Konopelko 2018). As of 2014, Kazakhstan had a population of 17.5 million people, ranking it as sixty-first globally in terms of population size.

However, the population density remains one of the lowest, with fewer than six individuals per square kilometer (Uteubayev 2016). Notably, Kazakhstan possesses the second-largest reserves of oil and ranks second in oil production among the former Soviet Union countries, trailing only Russia (Figs 1 and 2) (Kalyuzhnova et al. 2016).

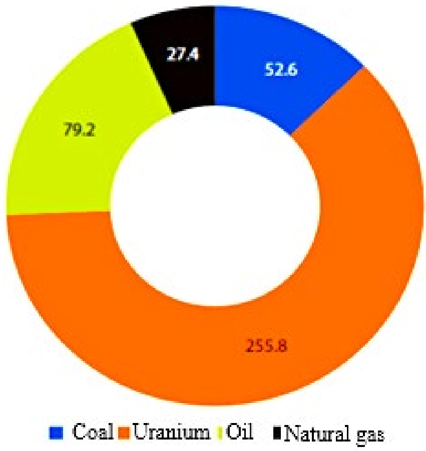

Fig. 1. Production of primary energy sources (in million metric tons of oil equivalent)
Source: World Bank calculations based on data published by the Committee on Statistics of the Republic of Kazakhstan

Rys. 1. Produkcja pierwotnych źródeł energii (w milionach ton metrycznych ekwiwalentu ropy naftowej)

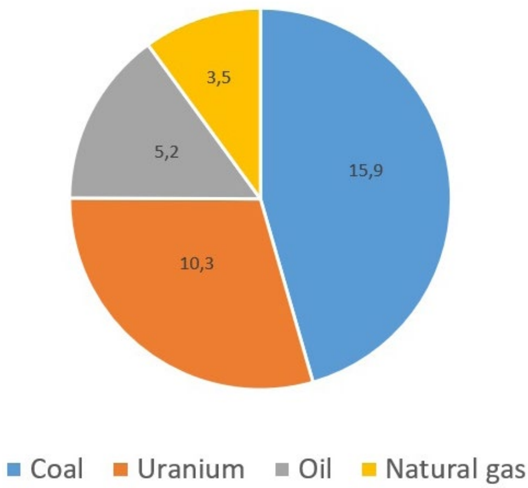

Fig. 2. Proven energy reserves (in billions of metric tons of oil equivalent)
Source: World Bank calculations based on data published by the Committee on Statistics of the Republic of Kazakhstan

Rys. 2. Potwierdzone zasoby energii (w miliardach ton metrycznych ekwiwalentu ropy naftowej)

In the past decade, the rise in natural gas production has contributed to increased volumes of oil production in Kazakhstan. This growth has been facilitated by the substantial use of natural gas for injection into oil fields. Consequently, the country has reduced its dependence on imported natural gas. However, gas consumption levels have remained relatively constant due to challenges in infrastructure and the costs associated with connecting remote settlements to production centers located in the northwest of the country. Being a landlocked nation, Kazakhstan is geographically distant from major global oil markets. As a result, the transportation of hydrocarbons is primarily accomplished through oil pipelines in order to facilitate export to international markets. Additionally, Kazakhstan serves as a transit country for the export of natural gas from Turkmenistan and Uzbekistan (Turganbayeva 2020; Bealessio et al. 2021).

The coal industry plays a prominent role in Kazakhstan's economy and is considered one of its leading sectors. The country boasts significant coal reserves, ranking among the top ten nations globally in this regard. The state balance accounts for coal reserves from forty-nine deposits, amounting to a total volume of 33.6 billion tons. Of these, 21.5 billion tons are bituminous coal, while 12.1 billion tons are lignite coal (Satayeva et al. 2022).

Kazakhstan also holds the second-largest explored natural uranium reserves worldwide. Approximately 12% of all explored uranium reserves globally are concentrated in Kazakhstan. In 2009, the country became the largest global producer of uranium, contributing nearly 40% to the world's total production (Ministry of Energy of the Republic of Kazakhstan 2023).

In 2012, energy consumption in Kazakhstan reached 2.8 quadrillion heat units. Coal accounted for the largest share in energy consumption, comprising 63%, followed by oil and natural gas, which constituted 18% and 16% of the consumption share, respectively (Mukhtarov et al. 2020).

1.1.1. Coal

The coal industry holds a critical position in Kazakhstan's economy, ranking among its largest sectors. Kazakhstan is a significant player in terms of coal reserves, placing it within the top ten countries globally. In the global ranking of coal reserves, Kazakhstan stands after countries such as China, the United States, Russia, Australia, India, South Africa, and Ukraine (Fig. 3) (Alimbaev et.al 2019).

Within Kazakhstan, the state balance incorporates coal reserves from forty-nine deposits, amounting to a total volume of 33.6 billion tons. This includes 21.5 billion tons of bituminous coal and 12.1 billion tons of lignite coal. The majority of coal deposits are located in Central Kazakhstan, primarily in the Karaganda and Ekibastuz coal basins, as well as the Shubarkol deposit. Furthermore, the Turgay coal basin is situated in Northern Kazakhstan (Fig. 4) (Coal industry of Kazakhstan 2022).

All of Kazakhstan's coking coal reserves are concentrated in the Karaganda region, providing the country with significant resources to meet domestic demands and export substantial quantities of coal products. However, the formation and development of the coal industry, along with other sectors in Kazakhstan's economy, have faced challenges since the dissolution of the Soviet Union (Askarova et al. 2022).

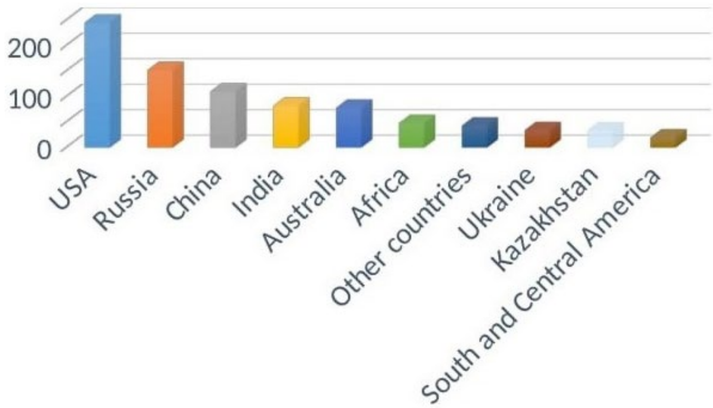

Fig. 3. Coal reserves in the world [billion tons]

Rys. 3. Zasoby węgla na świecie [mld ton]

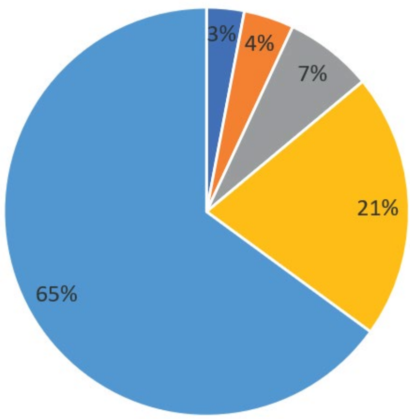

Fig. 4. Distribution of coal reserves in the Republic of Kazakhstan by regions

Rys. 4. Podział zasobów węgla w Republice Kazachstanu według regionów

1.1.2. Oil

The territory of Kazakhstan hosts more than 200 oil fields, spanning approximately 62% of the country's area. The majority of these fields are situated in western regions, including Atyrau, Mangystau, West Kazakhstan, and Aktobe. Among the noteworthy fields in terms of reserves are Kashagan (1–2 billion tons), Tengiz (0.75–1.125 billion tons), Karachaganak (1.35 trillion cubic meters of gas and 1.2 billion tons of oil), Uzen (1.1 billion tons), Kalamkas (67.6 million tons), and Zhetibay (68 million tons). In the global ranking of confirmed oil reserves, Kazakhstan holds the 12th position, with a total volume of 3.9 billion tons (Fig. 5) (Umarova et al.

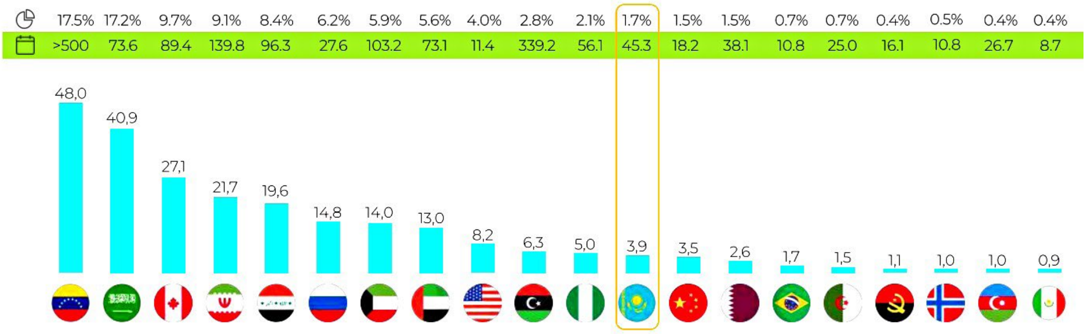

Fig. 5. Proved oil and condensate reserves by country [billion tons]
Source: Based on data from British Petroleum, US Energy Information Administration and Kazakhstan National Statistical Committee

Rys. 5. Udokumentowane zasoby ropy i kondensatu według kraju [miliardy ton]

2022). The country's natural gas reserves amount to 2.7 trillion cubic meters, ranking Kazakhstan fourteenth globally in this regard. At the current extraction rate, the confirmed oil and condensate reserves in Kazakhstan are projected to be sufficient for over forty-five years (The oil and gas sector 2020).

1.1.3. Natural gas

Kazakhstan has approved gas reserves of 3.9 trillion cubic meters, consisting of 2.6 trillion cubic meters of associated gas and 1.3 trillion cubic meters of natural (free) gas, according to the State Commission's assessment. However, the global industry information source, British Petroleum, estimates Kazakhstan's gas reserves at 1.3 trillion cubic meters, placing the country in the twenty-second position globally and third among the Commonwealth of Independent States (CIS) countries, after Russia and Turkmenistan. The discrepancies in estimates arise from the significant proportion of associated gas in Kazakhstan's reserves and variations in the calculation methods. Kazakhstan plans to transition to international standards for reserve estimation in the near future. Almost 98% of the explored gas reserves are concentrated in the western part of the country, with over 87% of them located in major oil and gas fields such as Tengiz, Kashagan, Karachaganak, Imashevskoye, as well as oil and gas condensate fields like Korolevskoye and Zhanazhol (Fig. 6) (Adilet zan 2022; Forbes 2021).

According to IHS (Information Handling Services) Markit, commercial gas production in Kazakhstan experienced growth from 2010 to 2020, reaching 34.8 billion cubic meters with an annual growth rate of 4%. However, further production growth is expected to be limited due to insufficient commercial incentives for gas producers. It is projected that by 2030, the production volume will reach thirty-six billion cubic meters, but then decline to thirty billion cubic meters per year by 2050. Nevertheless, the global model Nexant suggests that production levels of fifty

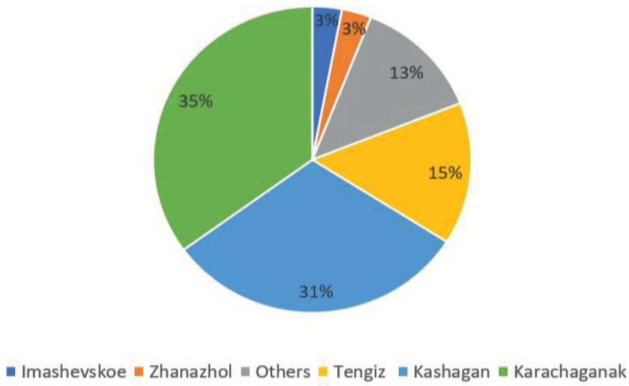

Fig. 6. Distribution of recoverable gas reserves by fields [in percent]

Rys. 6. Podział zasobów wydobywalnych gazu według złóż [w procentach]

billion cubic meters per year can be achieved through the development of new fields (Kazakhstan's National Energy Report 2021; Shi et al. 2016).

In order to prioritize domestic consumption and support growth, Kazakhstan may consider completely ceasing the export of natural gas. Natural gas plays a vital role in reducing emissions in the power sector and enhancing the flexibility of thermal power plants, particularly with the increasing share of renewable energy sources in the energy mix (Kaiser and Pulsipher 2007).

The expertise of Kazakhstani companies in oil refining is crucial for successful methane reforming projects. Additionally, gas and oil processing plants can serve as hubs for the development of a hydrogen economy by utilizing their production capabilities for "grey" hydrogen production and meeting the demand for hydrogen in hydrocarbon processing (Radelyuk et al. 2019).

1.1.4. Uranium

Kazakhstan holds the second-largest explored uranium reserves in the world, accounting for approximately 14% of the global total (Forbes 2022). The country's explored uranium reserves exceed 700,000 tons. In 2009, Kazakhstan became the leading global producer of uranium and has since maintained its position as a major player in the market, contributing about 40% of the world's uranium production. In 2021, uranium production reached 21.8 thousand tons, with a slight decrease to 21.3 thousand tons by the end of 2022 (Uranium and Nuclear Power in Kazakhstan 2023).

The discovery of the Kordai uranium deposit in 1951 marked the beginning of uranium exploration in Kazakhstan. Subsequently, significant findings were made in the late nineteen -sixties in the Shu-Sarysu and Ili basins, establishing Kazakhstan as the world's largest uranium province in terms of ore reserves. The country's uranium deposits vary in formation conditions and practical significance. Taking into account geological conditions, genetic characteristics, and geographic isolation, Kazakhstan can be divided into six uranium provinces: Shu-Sarysu, Syrdarya, North Kazakhstan, Caspian, Pribalkhash, and Ili (Fig. 7). Currently, out of the fifty-six

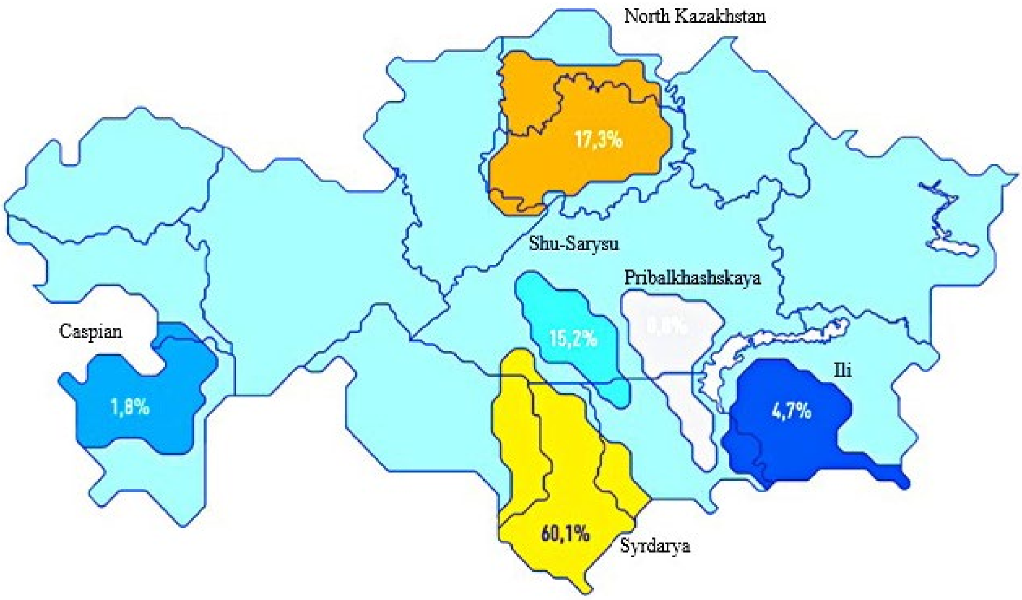

Fig. 7. Uranium deposits in Kazakhstan are grouped into six uranium provinces

Rys. 7. Złoża uranu w Kazachstanie podzielone na sześć prowincji uranu

deposits with uranium reserves, fourteen are in the development stage, while the remaining forty -two are in reserve (Kazakhstan Programs and Activities 2020; Collet et al. 2022).

2. Possible methods of hydrogen production in Kazakhstan

In Kazakhstan, hydrogen production is recognized as a strategic priority for the development of clean energy and sustainable growth. The country's abundant reserves of natural gas and renewable energy sources provide a strong foundation for hydrogen production (Kossalbayev et al. 2022).

The primary method of hydrogen production from natural gas is steam reforming, a process that involves decomposing natural gas into hydrogen and carbon dioxide. However, this process is associated with greenhouse gas emissions. Kazakhstan has the potential to implement various technologies to mitigate the carbon footprint of hydrogen production, including steam methane reforming, electrolysis, coal gasification, biomass gasification, solar hydrogen production and nuclear hydrogen production (Kopacz et al. 2019).

Hydrogen is classified into three categories based on the production method and associated emissions. "Gray" hydrogen is derived from fossil fuels like petroleum, gas, or coal through steam conversion, resulting in the release of carbon dioxide (CO_2). “Blue” hydrogen is produced from methane, with carbon dioxide utilization through the same steam conversion process. “Green” hydrogen is generated through water electrolysis, which involves the decomposition of water into hydrogen and oxygen using electricity obtained from renewable energy sources such as solar panels and wind turbines (Fig. 8) (Howarth et al. 2021; Hosseini et al. 2020).

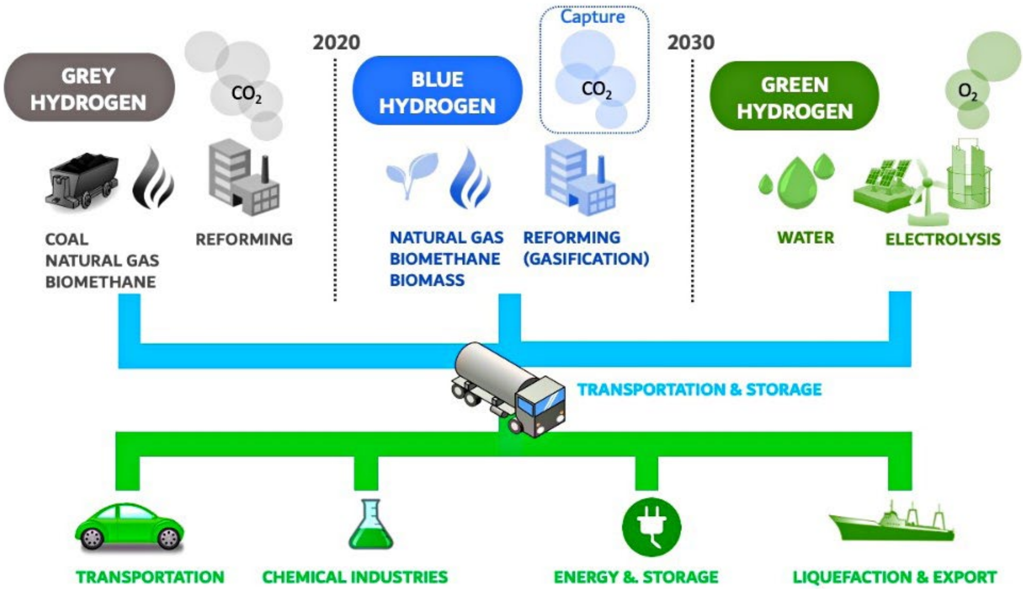

Fig. 8. The depiction of three methods for hydrogen (H2) production, each distinguished by a distinct color for identification purposes

Rys. 8. Przedstawienie trzech metod produkcji wodoru (H2), każda wyróżniona odrębnym kolorem w celach identyfikacyjnych

The generation of hydrogen involves the creation of hydrogen gas. Hydrogen gas can be derived from different sources including natural gas, coal, biomass, water and nuclear energy (Dawood et al. 2019). Presented below in this section are the frequently employed techniques for hydrogen production in Kazakhstan.

2.1. Steam methane reforming

Steam methane reforming is a chemical procedure employed to generate hydrogen gas (H_2) using natural gas or methane (CH_4) alongside steam (H_2O) and a catalyst. The process involves the following reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \text{ (endothermic)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (exothermic)}$$

$$\text{Overall reaction: } CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

This reaction occurs within a specialized device called a reformer, which is a high-temperature reactor operating at temperatures approximately between 800–1000°C and pressures of 20–30 bars. The reformer contains a catalyst that enhances the reaction rate and improves the efficiency of hydrogen production. Consequently, the process generates a gas mixture known as synthesis gas, comprising hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and water vapor (H_2O) (Więcław-Solny and Łabojko 2010). In addition, the synthesis gas obtained from steam methane reforming undergoes further processing to separate and purify hydrogen gas. The remaining carbon monoxide (CO) and carbon dioxide (CO_2) can be utilized for other applications, such as chemical production or as fuel for power generation (Więcław--Solny et al. 2009).

Steam methane reforming is the dominant method used worldwide for industrial hydrogen production, accounting for approximately 95% of the total global hydrogen production volume (Fig. 9) (Khan et al. 2021).

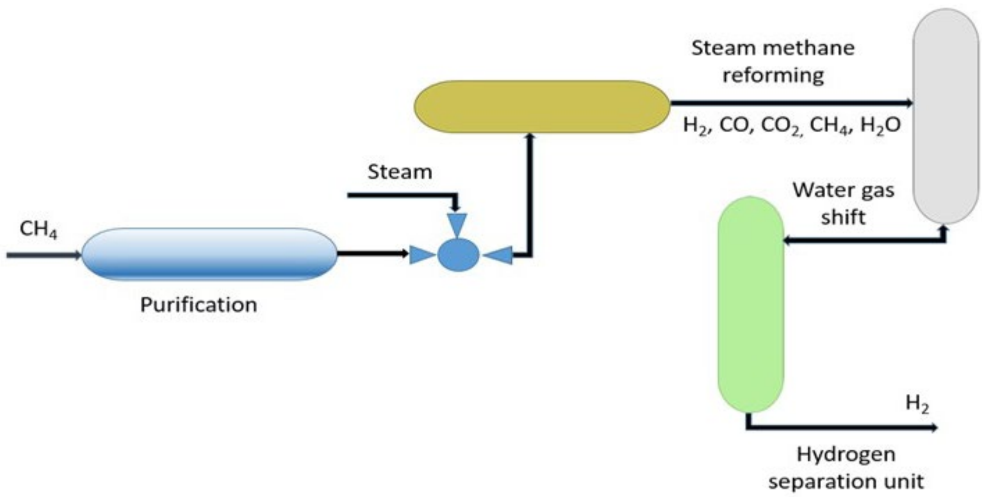

Fig. 9. Illustration outlining the conventional setup of a methane reforming unit employed in the generation of hydrogen

Rys. 9. Ilustracja przedstawiająca konwencjonalną konfigurację jednostki do reformingu metanu wykorzystywanej do wytwarzania wodoru

To achieve low-carbon hydrogen production from natural gas, it is crucial to implement carbon capture and storage (CCS) for the carbon dioxide (CO_2) generated during methane reforming. In Kazakhstan, a research project called KazCCUS was initiated in 2020, led by scientists Abuov and Lee. Its objective is to investigate suitable geological structures in sedimentary basins and assess their capacity for CCS (Leonzio et al. 2022).

Studies indicate that Kazakhstan possesses potential CO_2 storage opportunities in six sedimentary basins: the Caspian, Mangyshlak, Ustyurt, South Torgai, Chu-Sarysu, and Zaysan basins. The estimated total effective storage capacity for CO_2 in these basins is 204 megatons (Mt), 610 Mt, and 403 gigatons (Gt) for oil reservoirs, gas reservoirs, and saline aquifers, respectively. These findings demonstrate significant CCS potential in Kazakhstan, with the potential for implementing CCS technology in mature oil fields (Abuov et al. 2020).

According to the Carbon Neutrality Achievement Doctrine, CCS technologies are planned to be utilized from 2040 to 2060 to offset carbon emissions from the operation of thermal power plants. This will require a minimum of 50 Mt of CO_2 equivalent per year (Howie et al. 2022). Consequently, a substantial portion of the aforementioned potential can be harnessed for low-carbon hydrogen production from natural gas in Kazakhstan.

2.2. Electrolysis

The process of generating hydrogen through electrolysis involves the splitting of water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) by utilizing an electric current (Fig. 10). In Kazakhstan, water electrolysis is extensively utilized for the production of green hydrogen, which finds applications in various industries such as energy, chemical manufacturing and transportation. Moreover, Kazakhstan is actively exploring opportunities to export green hydrogen to places like China and Europe. Water electrolysis is among the methods employed for hydrogen production intended for export, and research and development endeavors are underway in this domain (Kumar et al. 2019; Ergazieva et al. 2020).

It is worth noting that water electrolysis is a complex technological process that necessitates substantial energy input. However, the advancement of renewable energy sources like solar and wind power can mitigate the adverse environmental impact and enhance the environmental sustainability of green hydrogen production through water electrolysis (Seidaliyeva et al. 2024).

In summary, Kazakhstan is making progress in the field of water electrolysis, with the aim of utilizing this technology for green hydrogen production to support environmental sustainability, foster the development of renewable energy sources and promote the hydrogen economy.

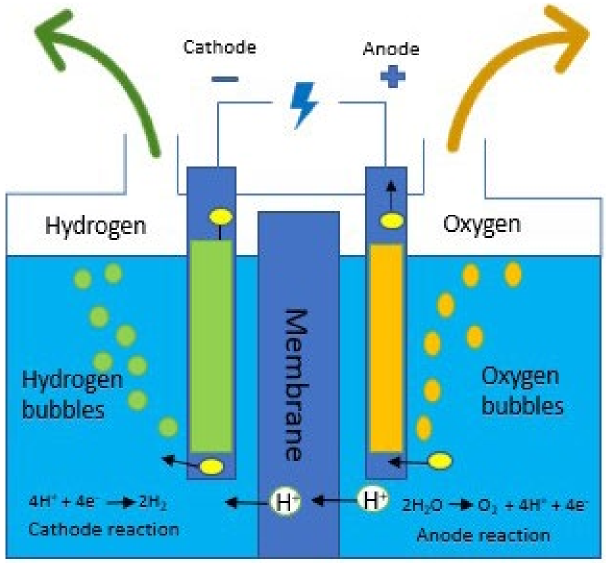

Fig. 10. Utilizing water electrolysis as an environmentally sustainable approach for generating green hydrogen

Rys. 10. Wykorzystanie elektrolizy wody jako zrównoważonego pod względem środowiskowym podejścia do wytwarzania zielonego wodoru

2.3. Coal gasification

Indeed, coal gasification can be utilized for hydrogen production. Coal gasification is a process that converts coal into a gas containing hydrogen, carbon monoxide and other gases. The gas can be further purified to obtain hydrogen. In the coal gasification process, coal is heated to high temperatures in the presence of oxygen and steam. This breakdown of coal yields its components, including hydrogen and carbon monoxide. The resulting gas mixture, referred to as syngas or synthetic gas, can then undergo processing to remove impurities and separate hydrogen from other gases (Fig. 11) (Liu et al. 2021, 2022).

In Kazakhstan, coal gasification is a strategic focus for the development of the energy sector. With substantial coal reserves in the country, gasification enables the efficient utilization of this natural resource for gas and electricity production (Tokmurzin et al. 2022).

Coal gasification in Kazakhstan offers several benefits. Firstly, it reduces reliance on imported natural gas, enhancing the country's energy independence. Secondly, coal gasification represents a cleaner method of coal utilization, as the purification of syngas helps reduce emissions of pollutants. Moreover, syngas can be utilized for the production of synthetic fuels and chemicals, contributing to the growth of the chemical industry in the country (Kerimray et al. 2018).

However, coal gasification also presents challenges and limitations. The process requires significant investments and advanced technological capabilities, which may impede the deployment of gasification projects due to financial and technical constraints. Additionally, coal gasi-

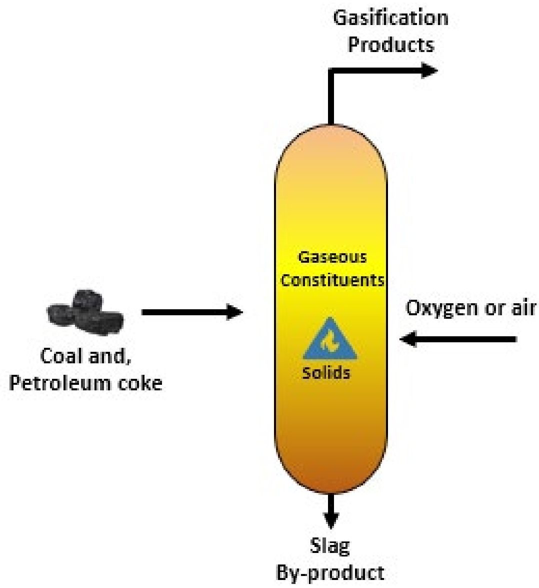

Fig. 11. Hydrogen production by gasification of coal

Rys. 11. Produkcja wodoru poprzez zgazowanie węgla

fication may necessitate additional waste management and environmental control measures to minimize its environmental impact (Fugiel and Burchart-Korol 2016).

Overall, coal gasification in Kazakhstan holds the potential for further development and can play a significant role in ensuring energy security and sustainable development in the country. However, successful implementation of gasification projects requires continued investment in research, development, and technological innovations, as well as careful attention to the environmental aspects of the process.

2.4. Biomass gasification

In a research study conducted by Asima Koshim and colleagues, the focus was on exploring the potential utilization of bioenergy resources in Kazakhstan. The findings of the study reveal that the bioenergy potential in the country amounts to approximately 485.36 MJ (equivalent to 16.582 million tons of coal), which represents around 30% of the country's current total energy consumption. The primary contributor to this potential is wheat residue, accounting for approximately 44% of the overall bioenergy potential. The study also highlighted an uneven distribution of bioenergy resources across different regions, influenced by climatic and topographical factors. The northern and southern provinces of Kazakhstan were identified as having the highest potential for bioenergy derived from wheat residues, while the central provinces with a dry climate exhibited the lowest potential. The western provinces, characterized by drought, soil salinity and degradation, were deemed unsuitable for biomass-based bioenergy production. Among the provinces engaged in agricultural cultivation, Akmola, Kostanay, and North Kazakhstan provinces, situated in the northern part of Kazakhstan, demonstrated the highest potential for biomass energy (Koshim et al. 2018).

An applicable approach in Kazakhstan is the utilization of biomass gasification for hydrogen production. Biomass gasification involves the conversion into syngas of organic materials such as wood, agricultural waste, plant residue and other biological waste. Syngas is a gas mixture comprised of various gases, including hydrogen (H_2) (Fig. 12). Following the gasification process, hydrogen can be separated from the gas mixture using different techniques, such as pressure swing adsorption, membrane separation or cryogenic distillation (Mukhambet et al. 2022; Chang et al. 2011).

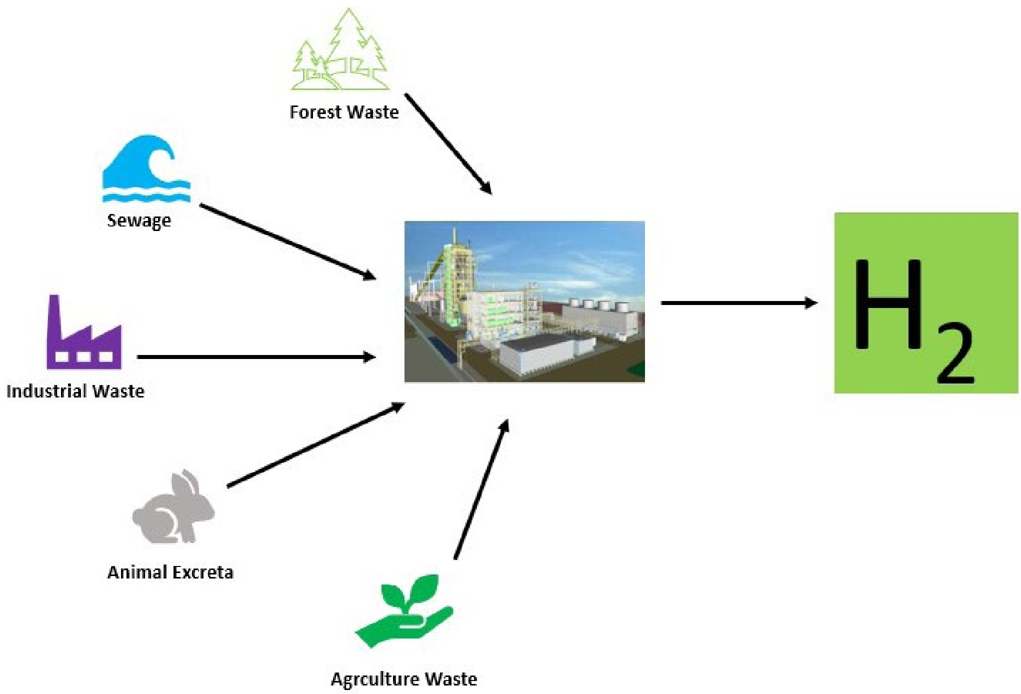

Fig. 12. Using biomass gasification as a means of converting waste into clean and renewable energy sources of green hydrogen

Rys. 12. Wykorzystanie zgazowania biomasy jako sposobu na przekształcenie odpadów w czyste i odnawialne źródła energii w postaci zielonego wodoru

Kazakhstan is actively engaged in research and development efforts in the field of biomass gasification for hydrogen production. This process involves the conversion of biomass into syngas and the subsequent separation of hydrogen from other components of the gas (Song et al. 2022).

Biomass gasification for hydrogen production offers several advantages, including the utilization of a renewable energy source, the reduction of greenhouse gas emissions and the improvement of the environmental situation. By utilizing biomass such as agricultural waste and plant residues, the reliance on unsustainable energy resources can be reduced (Alptekin et al. 2022).

It should be noted that there are certain limitations and challenges associated with biomass gasification for hydrogen production. The process demands significant energy input and investments in appropriate technologies. Ensuring consistent access to biomass sources can be complex in some regions. Moreover, effective waste management measures and the utilization of by-products generated during the biomass gasification process are crucial (Poluzzi et al. 2022).

2.5. Solar hydrogen production

Solar hydrogen production involves harnessing solar energy to split water molecules into hydrogen (H_2) and oxygen (O_2) through a process known as water splitting or photolysis. This method provides a sustainable and environmentally friendly approach to obtaining hydrogen, a valuable fuel and energy carrier (Starowicz et al. 2023).

There are various methods for solar hydrogen production, including photoelectrochemical (PEC) water splitting, photocatalytic water splitting, and direct solar water splitting. In the PEC method, a semiconductor material absorbs solar light and converts it into electrical energy, which initiates the water splitting reaction (Fig. 13). Photocatalytic water splitting utilizes a photocatalyst to absorb solar light and initiate the water splitting reaction (Zhang et al. 2022; Cheng et al. 2021; Sinha et al. 2022).

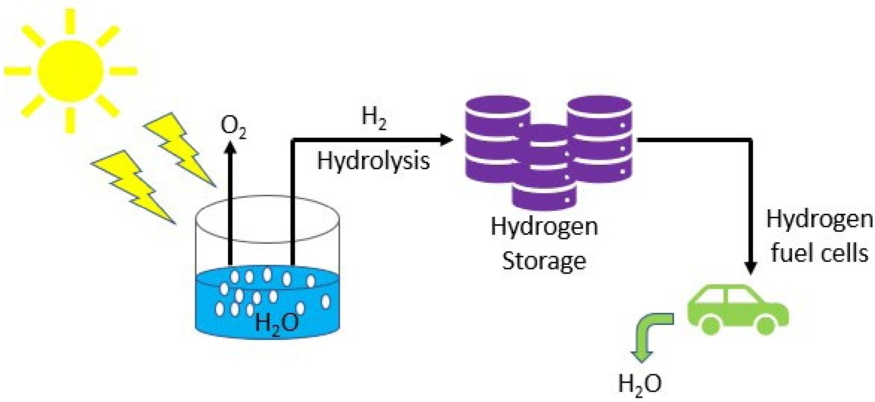

Fig. 13. Diagram of the basic principles of water splitting for a production green hydrogen

Rys. 13. Schemat podstawowych zasad rozdziału wody do produkcji zielonego wodoru

In Kazakhstan, specific projects and initiatives focusing on solar hydrogen production have been established. One such example is the fact that in 2019, the first commercial solar hydrogen production project was launched in Astana. The project incorporates a solar power plant that generates electricity from solar energy and a water electrolysis system that utilizes this electricity to produce hydrogen (Zhunussova et al. 2020).

Solar hydrogen production in Kazakhstan offers several advantages. Firstly, the country benefits from abundant solar energy resources due to its geographical location and climatic conditions, facilitating the efficient utilization of solar energy for hydrogen production. Secondly, solar hydrogen is a clean and renewable energy source that does not generate greenhouse gas emissions or harm the environment.

2.6. Nuclear energy hydrogen production

Nuclear hydrogen production involves utilizing nuclear energy to generate gaseous hydrogen (Fig. 14) (Pinsky et al. 2020). There are various methods employed in nuclear hydrogen production, including:

1. High-temperature electrolysis (HTE): Nuclear heat is utilized to produce high-temperature steam, which is then employed in an electrolyzer to split water molecules into hydrogen and oxygen.

2. Thermochemical water splitting: Nuclear heat drives a series of chemical reactions that lead to the decomposition of water molecules into hydrogen and oxygen.

3. Hybrid sulfur cycle: Nuclear heat initiates a sequence of chemical reactions that convert sulfuric acid into gaseous hydrogen.

4. Very high-temperature gas-cooled reactor (VHTR): Nuclear heat drives a gas turbine, which generates electricity. The electricity is then used to power an electrolyzer for hydrogen production (Karaca et al. 2020).

Nuclear hydrogen production offers several advantages over other methods. Nuclear energy is a reliable and environmentally clean energy source capable of providing sustainable heat for

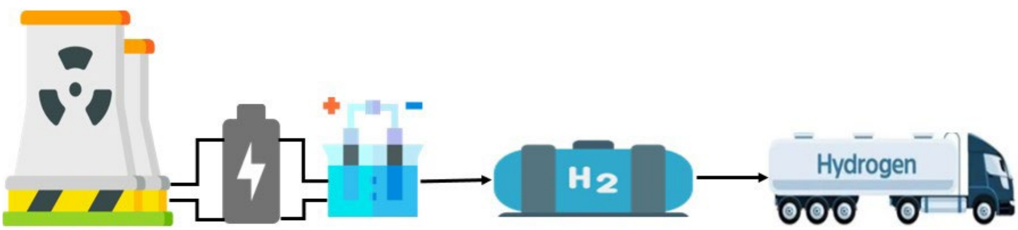

Fig. 14. Schematic representation of green hydrogen production using nuclear energy

Rys. 14. Schematyczne przedstawienie produkcji zielonego wodoru z wykorzystaniem energii jądrowej hydrogen production. The process enables the production of large quantities of hydrogen with minimal greenhouse gas emissions (Şahin et al. 2021). However, there are concerns surrounding the safety and security of nuclear power, as well as challenges associated with nuclear waste management (Ishaq et al. 2022).

As of now, Kazakhstan does not have any operational nuclear power plants (NPPs). However, the country has a history of constructing and launching research reactors for space programs since the mid-nineteen-seventies, and a national nuclear center was established in the nineteen-nineties. The future of nuclear energy in Kazakhstan is currently under discussion, with divided assessments. Approximately 60% of the population opposes the construction of NPPs, while others see them as a means to achieve national decarbonization goals and provide a reliable base load of low-carbon electricity generation (Tazhibayeva et al. 2009; Nuclear power in Kazakhstan 2022).

In the summer of 2022, it was announced that Kazakhstan had identified a location for its first nuclear power plant, which will be situated near Lake Balkhash in the town of Ulken, Almaty region. A preliminary list of suppliers has been compiled, including KHNP (Korea Hydro & Nuclear Power Co. Ltd), CNNC (China National Nuclear Corporation), Rosatom (Russian State Atomic Energy Corporation), and EDF (Électricité de France). The Kurchatov site on the Irtysh River is also being considered as a potential location for a second NPP (Sputnik Kazakhstan 2022).

It is worth noting that Kazakhstan is the largest producer of uranium, and the development of nuclear energy, both within the Balqash project and beyond, presents a long-term opportunity for the country's decarbonization efforts.

3. The possibilities for the development of green hydrogen energy in Kazakhstan

The development of "green" hydrogen holds significant importance for Kazakhstan, particularly in light of its trading partnership with the European Union (EU) and the EU's Green Deal. The EU's emphasis on green products and higher tariffs on non-green products will have a substantial impact on Kazakhstan's economy, making the development of "green" hydrogen crucial in the medium and long term (Abdildin 2021).

Kazakhstan has also signed a memorandum of understanding with the European Bank for Reconstruction and Development (EBRD) to achieve carbon neutrality in the country's energy sector by 2060. This collaboration further emphasizes the priority of developing "green" hydrogen in Kazakhstan's pursuit of carbon neutrality (Poberezhskaya et al. 2022).

Discussions are currently underway for the development of Kazakhstan's Carbon Neutrality Doctrine by 2060, which aims to achieve a significant reduction in CO_2 emissions in the energy sector. To accomplish this, Kazakhstan is focusing on “deep decarbonization” and maximizing the use of available technologies to achieve a 78% reduction in CO_2 emissions compared to 1990. The production of “green” hydrogen is seen as a promising direction to support this strategy (Aizhana et.al 2022).

To produce “green” hydrogen, certain requirements must be met, including access to water, land and renewable energy sources for water electrolysis. This involves ensuring access to water resources, establishing facilities for electricity generation from renewable sources like wind, solar power and hydropower, and securing land for constructing infrastructure related to “green” hydrogen production, such as renewable energy facilities, industrial buildings, and auxiliary structures (Mosca et al. 2020; Megía et al. 2021).

Kazakhstan has regions that are particularly suitable for the production of hydrogen. Scientists emphasize the Junggar Gate, located in the eastern part of the country near the China border, the Mangistau Peninsula in the west, and the Ereymentau wind corridor in the north as notable areas. Each of these regions has its own advantages. An example of these advantages is that the Junggar Gate is renowned for its constant and powerful winds, enabling the harvesting of seven times more energy compared to other nations worldwide. Additionally, this region benefits from its convenient proximity to transportation infrastructure connecting China and Russia. The Mangistau region, besides its ample water resources from the Caspian Sea, presents opportunities for harnessing both solar and wind energy. In the case of Ereymentau, situated in the Akmola region, it stands out due to its favorable conditions for the development of wind energy (Danenova et al. 2022).

Based on the data acquired from the project “Targets for the Protocol on Water and Health of the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Republic of Kazakhstan)” in 2017, the Republic of Kazakhstan was home to approximately 39,000 rivers and temporary watercourses. Among these, over 7,000 rivers have a length exceeding ten kilometers. The majority of Kazakhstan’s rivers are located within closed basins such as the Caspian and Aral Seas, as well as Lake Balkhash, Alakol, and Teniz. The Irtysh River is the only river that belongs to the Arctic Ocean basin (Issanova et al. 2018).

According to a study conducted by experts from the World Resources Institute entitled “World’s Ranking of Countries with the Highest Water Deficit in 2040” in August 2015, Kazakhstan holds the twentieth position among the thirty-three countries identified with a projected high level of water deficit (World Resources Institute 2015).

A World Bank study predicts a projected 16% decline in Kazakhstan’s water resources by 2030, reducing from 90 billion cubic meters to 76 billion cubic meters. In response to this, the government has implemented various measures including incorporating the term “adaptation” to climate change in the new Environmental Code, in order to mitigate the negative consequences and damages associated with climate change. However, effectively addressing this issue necessitates collective and conscientious efforts to conserve water resources (Tleuken et al. 2022; Kusmambetov et al. 2022).

Despite limited access to water, several major investors remain undeterred and actively pursue projects for the production of “green” hydrogen in Kazakhstan. In fact, various independent studies rank Kazakhstan among the top ten countries with significant potential for exporting "green" hydrogen (How will "green" hydrogen be produced in Kazakhstan 2022).

At present, investors are predominantly focused on exploring the central-western and western regions of the country for potential projects related to the production of "green" hydrogen and "green" ammonia. Some investors have already engaged in preliminary agreements concerning these regions in Kazakhstan, for example, SVEVIND AB, a German-Swedish company and a leader in renewable energy with over thirty years of experience in developing onshore wind farms, is currently pursuing a promising hydrogen project in Kazakhstan (Kazakh Invest 2015).

SVEVIND plans to construct wind and solar power plants with a combined capacity of 30 GW in the Mangystau region and utilize these resources to produce up to two million tons of hydrogen annually. The generated hydrogen, along with its derivatives like ammonia, will be exported to global markets and employed in various industrial sectors within the country (Ministry of Foreign Affairs of the Republic of Kazakhstan 2021).

On June 22, 2021, SVEVIND signed a Memorandum of Understanding with JSC "NC "KAZAKH INVEST". Currently, the process of reserving territories for the project is underway. The facility is anticipated to operate for several decades and attract substantial investments from international investors, amounting to several billion euros in Kazakhstan. Other significant projects for the production of "green" hydrogen are also being considered, as depicted in Figure 15 (Kazakh invest 2023).

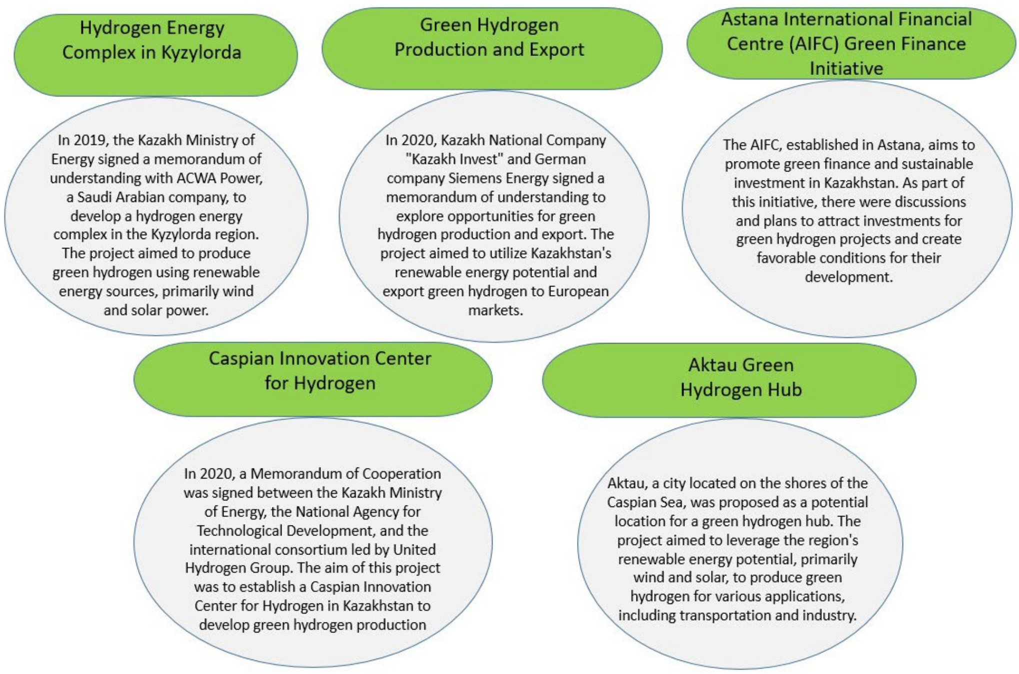

Fig. 15. Major projects for green hydrogen production in Kazakhstan

Rys. 15. Główne projekty produkcji zielonego wodoru w Kazachstanie

The production of environmentally friendly green hydrogen using electrolyzers relies on electricity generated exclusively from renewable energy sources (RES). The new Environmental Code of Kazakhstan defines RES to include solar 45, wind 29, hydro 47 and biogas 1 energy. Kazakhstan is currently witnessing a gradual rise in the proportion of RES within its energy sector (Kumar et al. 2022: Mouraviev 2021; Karatayev et al. 2016).

At present, wind and solar energy constitute 1.47 GW (6.2%) of the total installed capacity in the country, which amounts to 23.6 GW. The government has set a target to increase the RES capacity to 4.5 GW by 2028. Furthermore, according to the 2013 Green Economy Concept, the aim is for electricity generated from RES to account for 50% of the overall energy production by 2050 (Temirgaliyeva et al. 2020).

3.1. Strategic documents for the development of renewable energy sources (RES) and green energy in Kazakhstan

In December 2012, Kazakhstan's first president introduced a significant state document called the "Strategy Kazakhstan 2050" (Table 2). This strategy sets forth a vision for economic, social and political reforms with the aim of positioning Kazakhstan among the top thirty global economies. The objective is to establish a diversified economic model and expedite the country's shift towards low-carbon development. A year after the implementation of the Strategy Kazakhstan 2050, the "Concept of Kazakhstan's Transition to a Green Economy" was formulated, which offers more specific objectives for achieving low-carbon development (Adilet zan 2012; Association of Practicing Ecologists 2018).

The "Strategy 2050" has served as the foundation for the development and revision of the legislative framework in various sectors of Kazakhstan's economy. This has encompassed the creation of a new environmental code, the updating of laws and government programs related to energy efficiency, renewable energy sources (RES), emissions trading schemes, as well as plans for industrial development, the modernization of housing and communal services and other relevant areas (Development Strategy "Kazakhstan-2050" 2016).

Table 1. Strategy 2050: Goals of Low-Carbon Development

Tabela 1. Strategia 2050: Cele Rozwoju Niskoemisyjnego

	2020	2030	2050
RES in total electricity generation	3%	15% (an increase of 5% compared to the initially established indicators – May 2021)	50%
A decrease in energy intensity of GDP compared to the base level of 2008	–	30%	50%
Reduction of greenhouse gas emissions in electricity production.	15%	15%	40%

Table 2. Potential locations for the construction of wind farms

Tabela 2. Potencjalne lokalizacje pod budowę farm wiatrowych

Potential sites	Power [MW]
Dzungarskaya WPP	40
Shelekskaya WPP	140
Saryozekskaya WPP	140
Alakolskaya WPP	140
Karoyskaya WPP	20
Shengeldinskaya WPP	20
Kurdaiskaya WPP	20

Note: The table shows potential locations for wind power plant construction based on CarNet data, without dates, and Antonova, 2014. The regions are listed along with their respective potential in billion kilowatt-hours per year [kWh/year]. The last row represents the remaining regions with unspecified potential.

Kazakhstan actively participates in the international arena while concurrently advancing its regulatory framework. A notable event in this regard was the hosting of the international exhibition "EXPO-2017: Future Energy" in the capital city of Astana, Kazakhstan (refer to Figure 16). Taking

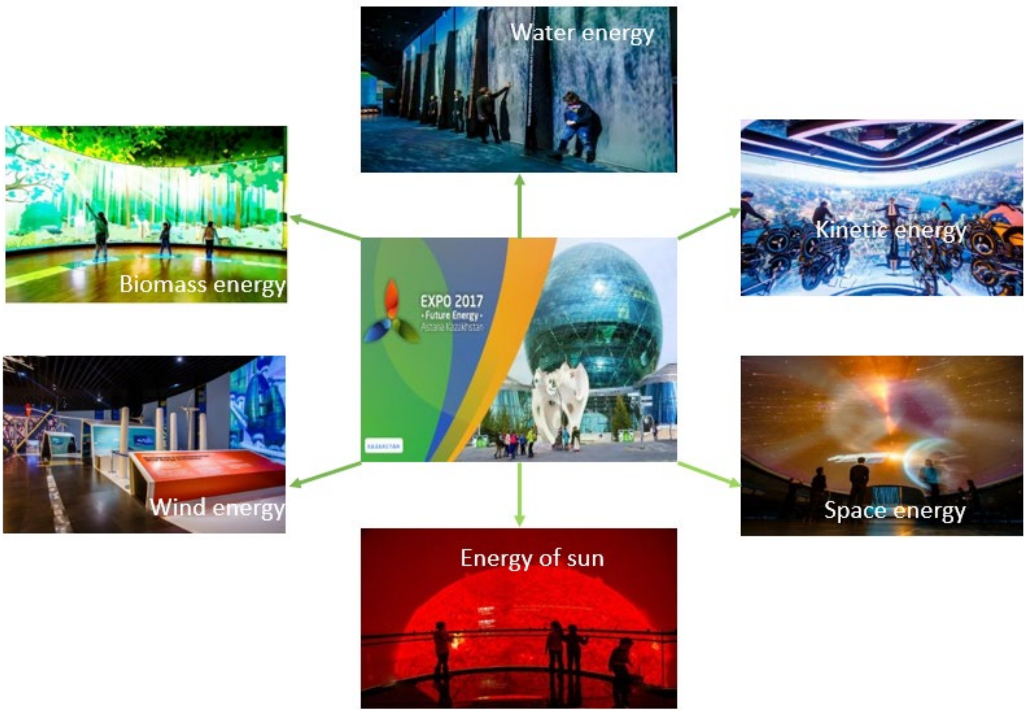

Fig. 16. Expo 2017 Astana – Future Energy

Rys. 16. Expo 2017 Astana – Energia przyszłości place from June 10 to September 10, 2017, the exhibition focused on energy and its future, with a significant emphasis on alternative energy sources, sustainable development, and energy efficiency. Organized by the International Bureau of Exhibitions (BIE), the “EXPO-2017: Future Energy” exhibition became the largest event of its kind in Central Asia. It brought together participants from over one hundred countries, including governments, international organizations, businesses and the general public. The exhibition showcased innovative technologies and projects aimed at enhancing energy efficiency, utilizing renewable energy sources, implementing energy management strategies and reducing greenhouse gas emissions (Golovina et al. 2021; Kadirbayeva et al. 2016). This event was highly successful and played a crucial role in raising awareness about energy-related issues and exploring innovative solutions for sustainable development in the future.

In 2016, Kazakhstan made significant advancements in its climate policy by ratifying the Paris Agreement on climate change and submitting its nationally determined contribution (NDC). Within the NDC, Kazakhstan established the following objectives:

1. Unconditional target: Reduce greenhouse gas (GHG) emissions by 15% by 2030 compared to the 1990 level.

2. Conditional target: Reduce GHG emissions by 25% by 2030 compared to the 1990 level, contingent upon additional international investments, access to low-carbon technology transfer mechanisms, the utilization of the Green Climate Fund and grant assistance for countries with transitioning economies (Kerimray et al. 2018).

To attain these ambitious goals and implement the necessary measures, Kazakhstan actively engages in collaborations with various international institutions, including the United Nations Development Programme (UNDP), the Global Environmental Facility (GEF), the European Bank for Reconstruction and Development (EBRD), the Asian Development Bank (ADB), the World Bank and other donor organizations like USAID. Analytical centers such as EY, KPMG, and PwC also play a role in these collaborations. This concerted effort has already yielded visible results and holds strategic importance in fulfilling the commitments outlined in the NDC (Tleuken et al. 2022).

In December 2020, during the Climate Ambition Summit, the President of Kazakhstan unveiled a new objective for the country: achieving carbon neutrality by 2060. This goal necessitates substantial financial resources, the widespread adoption of advanced technologies and revisions to existing laws on renewable energy sources and energy efficiency to facilitate the decarbonization of the economy (Poberezhskaya et al. 2022). In the following section, we will examine in detail the existing renewable energy sources such as wind energy, solar energy and hydropower used in Kazakhstan for green hydrogen production.

3.2. Renewable Energy Sources

Based on information provided by KEGOC and Kazenergy, hydroelectric power plants (HPPs) contributed to 8.8% of the total electricity production in Kazakhstan in 2020. Solar power plants accounted for 1% of the production, while wind power plants contributed 1.2%. It is worth noting that Kazakhstan possesses significant untapped potential in renewable energy sources (RES), particularly in wind and solar energy (JSC "KEGOC" Annual Refort 2021; Boute 2020).

The efficiency of utilizing renewable energy sources (RES) varies across different regions in Kazakhstan. The Atyrau region demonstrates the highest utilization coefficient of installed capacity (UCIC) for wind energy, while the Almaty region showcases the highest UCIC for solar energy. On average, the country's UCIC stands at 24% for wind energy and 16% for solar energy (Bespalyy 2021).

According to the Deputy Minister of Energy in 2017, Kazakhstan's wind energy potential surpasses the country's current electricity consumption by approximately ten times, thanks to its expansive territory. In the baseline scenario outlined in the Doctrine, electricity production from renewable energy sources, including hydroelectric power plants (HPPs), is projected to increase by 2.2 times (15.6 terawatt-hours) between 2017 and 2040. In the carbon-neutral scenario, this production is expected to rise nearly 15 times (161 terawatt-hours) (Tengri News 2013; Doctrine (strategy) of achieving carbon neutrality of the Republic of Kazakhstan until 2060, 2021).

ESMAP estimates the average theoretical potential of photovoltaic energy in Kazakhstan to be 3.82 kilowatt-hours per square meter. To meet the electricity demand using photovoltaic stations, only 0.05% of the country's territory would be sufficient. The levelized cost of electricity (LCOE) for solar power generation is estimated to be around $0.12 per kilowatt-hour (University of central Asia 2022).

In a study conducted by Dmitry Bogdanov et al. (2018), Kazakhstan's transition to 100% renewable energy by 2050 was analyzed. The modeling results, using the LUT Energy System Transition modeling tool, suggest that Kazakhstan can achieve this transition, with solar energy becoming the primary source generating over 50% of the energy in the system.

In research conducted by Salman Ahmad et al. (2017), a multi-criteria assessment method was employed to analyze renewable and nuclear resources for electricity production in Kazakhstan. The study determined that hydroenergy emerged as the most favorable resource, followed by solar energy. Wind energy and nuclear energy ranked third and fourth, respectively, while biomass was deemed the least attractive option. Consequently, the research suggests that the government of Kazakhstan should prioritize the development of hydro, solar and wind technologies, while putting nuclear energy and biomass on hold.

3.2.1. Wind energy

Wind energy is experiencing rapid development as a renewable energy source in Kazakhstan. The country's favorable climatic conditions and widespread distribution of wind resources have contributed to its wide implementation. Kazakhstan has wind corridors with wind speeds exceeding 5 m/s, which are ideal for operating wind turbines. The regions with the highest wind energy potential include the Caspian region, and central and northern Kazakhstan, as well as southern and southeastern Kazakhstan (Mukhamediev et al. 2019; Jianzhong et al. 2018; Turgali et al. 2021).

The Ministry of Industry and New Technologies of Kazakhstan estimates the wind energy potential in the country to be around 920 billion kilowatt-hours of electricity per year. The “Kazakhstan – Wind Energy Market Development Initiative” project has identified an average wind speed of 5–6 m/s throughout the country, making it suitable for successful wind power plant projects. As part of this initiative, a wind atlas has been compiled, highlighting areas with high wind speeds capable of generating from 0.929 to 1.82 billion kilowatt-hours of electricity per year (Fig. 17) (Kazakhstan truth 2017; The potential of wind energy in Kazakhstan 2020).

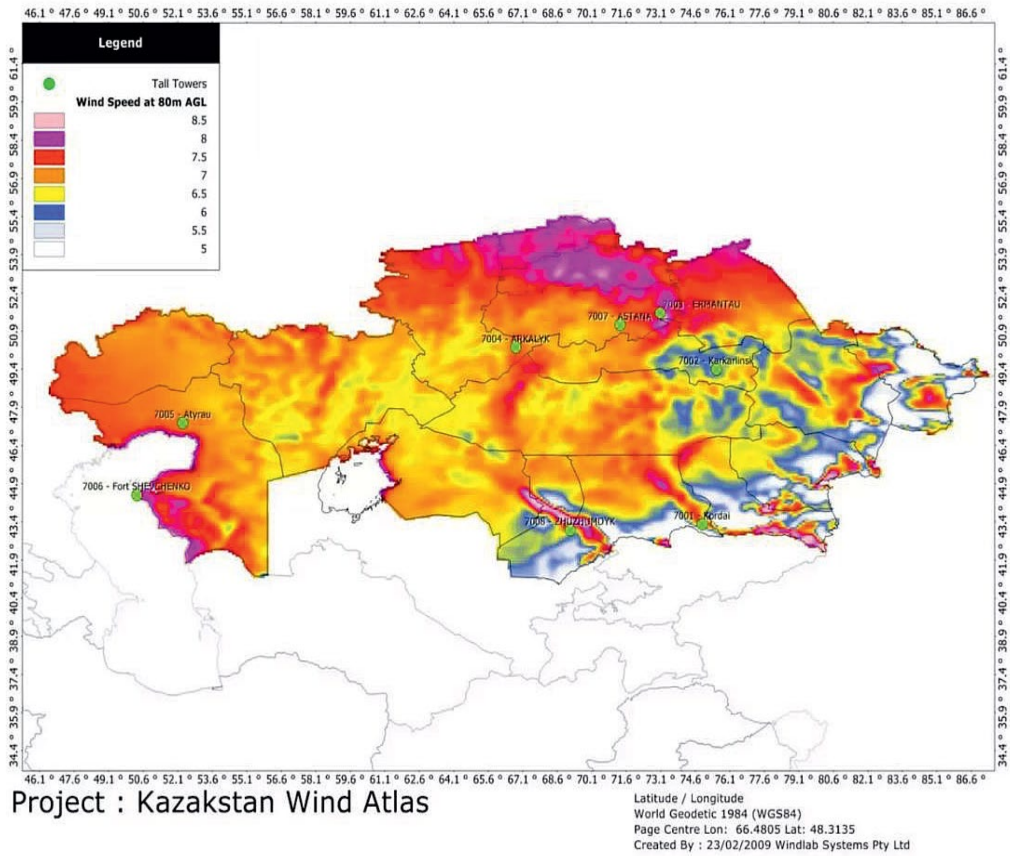

Fig. 17. Wind Atlas of Kazakhstan
Source: Parsons Brinckerhoff

Rys. 17. Atlas wiatru Kazachstanu

The Energy Development Program until 2030, implemented by the Ministry of Industry and New Technologies, has identified ten locations for the construction of large-scale wind power plants. Among these, the Jungar Corridor stands out as one of the most promising areas with a potential of 17 billion kilowatt-hours per square meter (Official information resource 2022;

Laldjebaev et al. 2021). Table 3 provides information on potential locations for wind power plant construction based on available meteorological data within the Energy Development Program until 2030.

TABLE 3. Solar illumination of a horizontal surface [kWh/m^2]

TABELA 3. Oświetlenie słoneczne powierzchni poziomej [kWh/m^2]

	Shevchenko	Aral Sea	Almaty
January	44	55	49
Februrary	64	85	65
March	108	131	101
April	153	171	136
May	201	228	182
June	208	236	199
July	209	231	211
August	188	204	186
September	142	155	141
October	91	95	91
November	50	52	52
December	34	39	37
Annual	1,492	1,682	1,450

3.2.2. Solar energy

Solar energy has immense potential as a renewable energy source in Kazakhstan thanks to its low population density and favorable climatic conditions, particularly in the southern region of the country. With a range of sunshine hours from 2,200 to 3,000 per year, the southern part of Kazakhstan receives intense solar radiation during the summer months (June-August). This region benefits from a high number of daylight hours with solar radiation reaching 83–96% of the maximum possible value due to its geographical location. In contrast, the northern part of the country receives around 2000 sunshine hours annually.

Cities in the southern region, such as Kyzylorda and Shymkent, receive approximately 2,936 and 2,892 sunshine hours per year, respectively, making them suitable for meeting the electricity demand in that part of Kazakhstan. By comparison, other countries like Vietnam have an average of 2,200 sunshine hours, China has 2,500, and countries like Germany, the United Kingdom, Norway, and Japan have less than 1,000 sunshine hours per year (Terehovics et al. 2017; Minazhova et al. 2023; Nurseiit et al. 2018).

As the largest country in Central Asia, Kazakhstan possesses a vast potential for the development of solar energy. The amount of solar radiation in the country ranges from 1,300 to 1,800 kilowatt-hours per square meter per year (Fig. 18) (Nurlankyzy et al. 2016). This significant solar resource provides an opportunity for Kazakhstan to harness solar energy as a sustainable and reliable source of electricity generation.

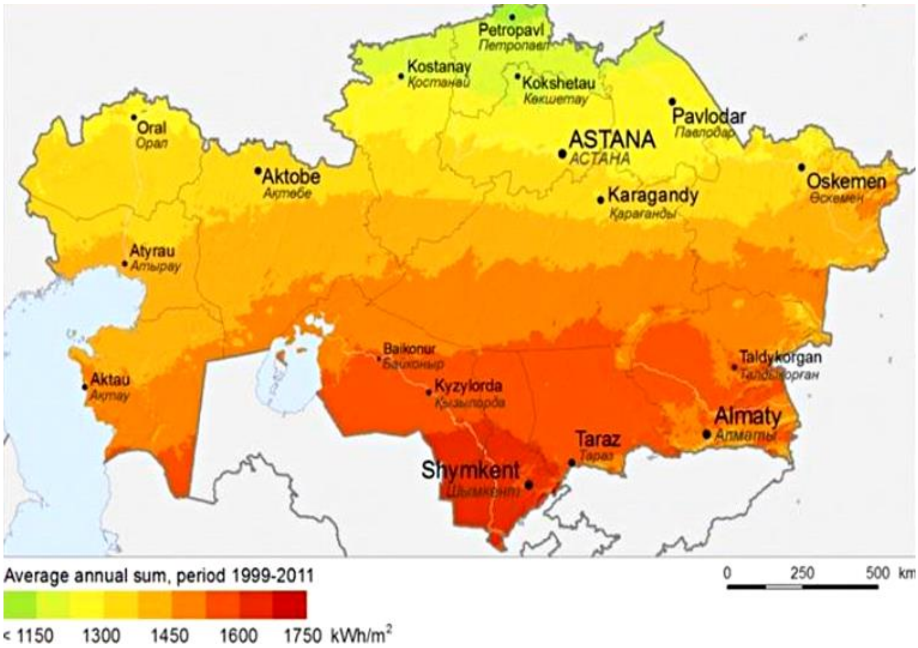

Fig. 18. Kazakhstan Sun Atlas
Source: World Bank 2019

Rys. 18. Atlas słońca Kazachstanu

Based on the data, more than 50% of the land in Kazakhstan is suitable for the installation of solar power plants. However, until recently, the country had not fully tapped into the potential of its solar resources for generating electricity. At present, Kazakhstan is actively engaged in the development of solar energy technologies, including the manufacturing of photovoltaic modules using domestically sourced silicon. Given the substantial silicon reserves within the country, estimated at 85 million tons, the local market has initiated the production of solar panels using Kazakh silicon. To this end, the recently inaugurated "Astana Solar" facility in Astana is focused on manufacturing photovoltaic modules. The plant intends to produce solar panels utilizing Kazakh silicon, starting with an initial capacity of 50 MW, which can potentially be expanded to 100 MW (Karatayev et al. 2017; Klinovitskaya et al. 2019; Kazakhstan truth 2013).

3.2.3. Hydropower

Hydropower plays a crucial role in Kazakhstan's electricity generation, ranking as the second most important source after coal. On average, the combined hydropower plants in the country produce approximately 8–9 billion kilowatt-hours of electricity annually. However, the total hydropower potential of Kazakhstan is estimated to be around 170 billion kilowatt-hours per year. Out of this estimate, it is technically feasible to harness about 62 billion kilowatt-hours, and economically viable to utilize approximately 30 billion kilowatt-hours of energy annually. These figures highlight a significant potential for investment in hydropower projects within the country (Karatayev et al. 2017).

The primary regions in Kazakhstan with notable hydropower potential are geographically situated as follows:

1. The Irtysh River basin, which houses prominent hydropower plants like Bukhtarma, Shulbinsk, and Ust-Kamenogorsk.

2. The Ili River basin, where the Kapchagay and Moinak hydropower plants are located.

3. The Syr Darya, Talas, and Chu River basins, among which the Shardara hydropower plant stands out (Kukeyeva et al. 2018).

These regions possess substantial hydropower potential, presenting favorable opportunities for the development of hydropower projects in Kazakhstan (Park et al. 2021).

The rivers Charyn, Chilik, Karatal, Koksu, Tentek, Khorgos, Tekes, Talgar, Usek, Aksu and Lepsi are among the potentially suitable rivers for constructing large-capacity hydroelectric power stations in Kazakhstan. At present, hydropower contributes approximately 9% to the total energy production in the country. Despite the uneven distribution of hydropower resources, Kazakhstan holds significant potential for developing hydroelectric power stations (Azimov et al. 2022; Parkhomchik 2020). The energy balance of the country relies on both Soviet-era and post-Soviet hydroelectric power stations. As of 2016, the average age of equipment in Kazakh hydroelectric power stations is 36.5 years. The Leningor Cascade, the first hydroelectric power station in Kazakhstan with an installed capacity of 13.8 MW, was established in 1928 and remains operational. Among the large power stations, the Moynak Hydroelectric Power Station stands as the most modern, commissioned in 2011 and operating at full capacity (300 MW) since 2012. In 2013, several small hydroelectric power stations were commissioned in the Almaty and Zhambyl regions (Barrett et al. 2017).

The government of Kazakhstan is actively exploring new opportunities and potential territorial resources to identify additional sites for the construction of hydroelectric power stations (Vechkinzova et al. 2021). Within the Development Plan for the Hydroenergy Sector of the Republic of Kazakhstan, spanning from 2020 to 2030, several activities were outlined and approved by the Deputy Prime Minister on September 4, 2020. These activities include:

- Introducing new capacities at large hydroelectric power stations, amounting to 1,300 MW.
- Introducing new capacities at small hydroelectric power stations, totaling 1,500 MW.
- Increasing the installed capacity at existing hydroelectric power stations by 464 MW.
- Completing ongoing projects with a combined capacity of 90 MW.

- Constructing seventy prospective hydroelectric power stations (Development plan of the hydropower industry of the Republic of Kazakhstan for 2020–2030, 2020).

4. The potential for the establishment of low-carbon hydrogen in Kazakhstan

Kazakhstan possesses a considerable potential for producing low-carbon hydrogen, primarily due to its abundant reserves of natural gas. Low-carbon hydrogen refers to hydrogen production processes that generate minimal greenhouse gas emissions, particularly carbon dioxide (CO_2). The applications of low-carbon hydrogen are diverse and encompass its use as an environmentally friendly fuel for automobiles, aviation and maritime transport, as well as in industrial processes and fertilizer production (Gray et al. 2021). Within Kazakhstan, the production of low-carbon hydrogen primarily occurs through two methods: water electrolysis utilizing renewable energy sources and steam methane reforming of natural gas, followed by carbon capture and storage (CCS) (Antonini et al. 2020).

Kazakhstan is committed to becoming a pioneer in the production of low-carbon hydrogen and is actively engaged in fostering local and international collaborations in this sector. In 2021, the country became a member of the Hydrogen Council, an international organization that unites governments, businesses and academic institutions to drive advancements in the hydrogen energy market. Prominent global companies and organizations have shown keen interest in partnering with Kazakhstan for the production and export of low-carbon hydrogen. The development of low-carbon hydrogen production in Kazakhstan is expected to yield multiple benefits, including the reduction of greenhouse gas emissions, the creation of new job opportunities, and a boost to the country's overall economic growth (Agumbayeva 2016; Raihan et al. 2022).

The generation of low-carbon hydrogen necessitates the utilization of resources and energy inputs, including renewable energy derived from sources like RE, hydroelectric power plants, nuclear power plants, natural gas or biomethane, coal through gasification, as well as water and other materials. When fossil fuels are used, it becomes imperative to establish an industry focused on carbon capture and long-term storage (Yu et al. 2021; Bhavsar et al. 2023).

4.1. The capacity of Kazakhstan to produce low-carbon hydrogen

In this section, we present an analysis of the resource potential for low-carbon hydrogen production in Kazakhstan until 2040 using various technologies, as provided by the United Nations Economic Commission for Europe (UNECE) (UNECE 2023).

4.1.1. Conjectures and assessments made for the study

After conducting a thorough analysis in this review, it has become evident that Kazakhstan possesses resources suitable for hydrogen production. These resources include the utilization of water electrolysis powered by electricity generated from renewable energy sources (RES), as well as electricity generated from nuclear power plants (NPPs) once they are operational. Furthermore, if the technology is developed, there are resources for hydrogen production through methane reforming with carbon capture and storage (CCS) capabilities.

In the year 2040, the resource potential for hydrogen production is determined by several factors (UNECE 2023):

A. The technical and economic capabilities of wind and solar power generation, along with other renewable energy sources (RES).

B. The feasible portion of RES-generated electricity that can be allocated for hydrogen production instead of being used directly in Kazakhstan's energy sector or exported to neighboring countries.

C. The potential growth in natural gas extraction.

D. The economically justified proportion of natural gas that should be allocated for hydrogen production instead of being directly consumed within the Kazakh economy or exported.

E. The feasibility of implementing carbon capture and storage (CCS) technology for the long-term storage of carbon dioxide produced during hydrogen production from natural gas.

Due to the present level of uncertainty, precise calculations of these parameters are not possible. However, an assessment of the resource potential can be made by considering them at minimum and maximum levels. This study incorporates two scenarios (UNECE 2023):

1) In the minimum scenario:

A. 30% of the projected increase in electricity generation from solar and wind energy between 2020 and 2040, as outlined in the baseline scenario of the Doctrine, is allocated for hydrogen production.

B. 30% of the anticipated growth in natural gas extraction, as forecasted by IHS Markit, is dedicated to hydrogen production.

C. 5% of the annual output of new nuclear power plants is utilized for hydrogen production, assuming the remaining electricity generated by NPPs is utilized within the energy system.

2) In the maximum scenario:

A. 50% of the projected increase in electricity generation from solar and wind energy between 2020 and 2040, as defined in the "carbon neutrality" scenario of the Doctrine, is utilized for hydrogen production.

B. 30% of the anticipated growth in natural gas extraction, as projected by the Nexant model, is directed towards hydrogen production.

C. 8.3% of the annual output of new nuclear power plants is allocated for hydrogen production, assuming that the remaining electricity generated by NPPs is used within the energy system.

In both scenarios, it is assumed that water electrolysis for hydrogen production requires 55 kWh of electricity per kilogram of hydrogen, while methane reforming for hydrogen production requires 5.3 cubic meters of natural gas per kilogram of hydrogen. Additionally, it is considered that during the reforming process, 10 kg of CO_2 emissions are produced per kilogram of hydrogen, and this must be captured and stored (UNECE 2023).

4.2. Resource capacity

The assessment results are presented in Figure 19. Based on the adopted assumptions, the primary long-term prospects for hydrogen production in Kazakhstan revolve around two methods: water electrolysis utilizing renewable energy sources (RES) and methane reforming with carbon capture and storage (CCS) technology (UNECE 2023).

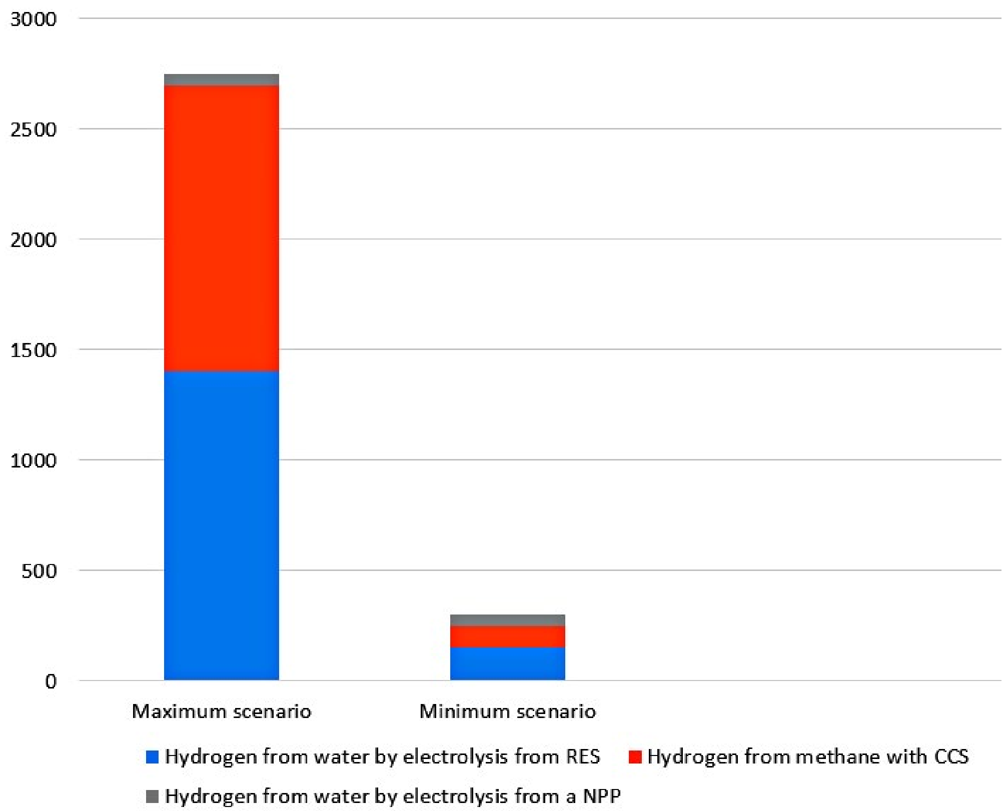

Fig. 19. Projected resource potential of hydrogen production in Kazakhstan by 2040 [thousand tons per year]

Rys. 19. Prognozowany potencjał zasobowy produkcji wodoru w Kazachstanie do 2040 roku [tys. ton rocznie]

These prospects are influenced by the country's establishment of ambitious goals and the increasing momentum in the development of renewable energy sources (RES). Additionally, the presence of significant proven natural gas reserves and their increasing extraction contribute to these factors. However, a crucial requirement and limitation is the advanced development of the carbon capture and storage (CCS) sector. Even in the most conservative scenario, the construction of CCS facilities with a total capacity of 1 million tons of CO_2 per year is necessary, along with the implementation of projects combining RES and electrolysis (UNECE 2023).

4.2.1. Cost estimation

According to estimates by ERIRAS (Energy Research Institute of the Russian Academy of Sciences 2022), the production cost of low-carbon hydrogen using electricity generated from new nuclear power plants (NPPs) in Russia could be approximately $4 per kilogram, considering their operation for sixty years. This estimate could serve as a minimum value for the conditions of NPPs in Kazakhstan, assuming the possibility of using Russian technologies for NPP construction in the country within the same timeframe. It's important to note that reducing the payback period to twenty to thirty years may result in increased costs for both electricity and hydrogen (Kumekov et al. 2013).

Considering the expected cost of electricity from new renewable energy sources (RES), such as solar and wind energy ($0.05 per kilowatt-hour) based on estimates from the International Energy Agency (IEA), the cost of hydrogen production can range from $3.5 to $5 per kilogram. This calculation is based on parameters such as full load of electrolyzers for 1,500–2,000 hours per year, electrolyzer cost (CAPEX) at $450 per kilowatt, and a refinancing rate of 8% (Renewable Electricity 2022).

The cost of hydrogen production from natural gas depends on the cost of feedstock (in this case, natural gas production in Kazakhstan as a gas-producing country) and the cost of carbon capture and storage (CCS). According to IEA estimates from 2019, the cost of gas in gas-producing countries accounted for approximately 30% of the cost of "blue" hydrogen. Assuming a production cost of gas at $100 per thousand cubic meters, the estimated cost of producing "blue" hydrogen ranges from $1.5 to $2.0 per kilogram of hydrogen (Soja et al. 2023; Brändle et al. 2021).

4.3. Shipping capabilities and restrictions for export-focused hydrogen projects

Due to its lack of direct access to open seas, exporting hydrogen from Kazakhstan requires a combination of land and maritime transportation. The distance from Aktau, the center of the Mangystau region where the Svevind project is being considered, to the port of Rotterdam in the

Netherlands is 7,700 kilometers, and to the port of Kobe in Japan is 17,500 kilometers. These distances are greater than those of similar hydrogen projects in the MENA region. By comparison, the NEOM Green Hydrogen project in Saudi Arabia, with a capacity of 4 GW, requires 6,500 kilometers to Rotterdam and 13,800 kilometers to Kobe. The geographic location of Kazakhstan poses limitations on the competitiveness of similar projects (Kanapiyanova 2019).

The nearest capital of an EU member state, Sofia, is located at a distance of 4,100 kilometers from Aktau by land transport, passing through Russia, Georgia and Turkey. This distance is greater than that for Azerbaijan, which already has gas pipelines like TAP and TANAP reaching European countries. Therefore, Kazakhstan's location relative to the future hydrogen market in Europe, which is expected to import up to 10 million tons of hydrogen per year by 2030, can be considered non-competitive. Developing an export strategy may require a more detailed study of these transportation routes, considering the competitiveness of Kazakhstani suppliers based on cost, carbon footprint, and the origin of hydrogen (with the European market favoring green or renewable hydrogen) (Sea Highways of the Black and Caspian Seas 2009).

Kazakhstan benefits from its border sharing with China, and the distance from Aktau to Urumqi, the largest industrial center in the Xinjiang Uygur Autonomous Region of China, is approximately 2,800 kilometers via land transport. The Central Asia-China gas pipeline, which passes through Kazakhstan, connects to the Chinese "West-East" gas pipeline in Khorgos, located on the border between Kazakhstan and the Xinjiang Uygur Autonomous Region of China (Harutyunyan 2022). This geographical proximity and existing infrastructure create opportunities for exporting hydrogen to China using pipeline, road and rail transportation methods.

5. Current and potential pilot projects in Kazakhstan

Kazakhstan is actively engaged in the development of pilot projects in the field of hydrogen with the aim of becoming one of the leaders in this area in Central Asia. This section highlights current and future pilot projects related to the utilization of hydrogen.

5.1. Current pilot projects

The low-carbon development program "KazMunayGas" has established the Center of Competence for Hydrogen Energy (KMG 2022), which is the leading oil and gas company in Kazakhstan. This program, spanning from 2022 to 2031, encompasses the following key areas:

- Enhancing KazMunayGas' scientific research and development capabilities in the realm of low-carbon technologies, including hydrogen and CCUS (carbon capture, utilization, and storage).

- Evaluating the potential for producing blue hydrogen, which involves generating hydrogen from natural gas while simultaneously capturing and storing carbon emissions.
- Advancing technologies for hydrogen storage and transportation, which are critical aspects for its utilization in the energy sector.

In September 2022, the Center of Competence for Hydrogen Energy actively collaborates with several universities in Kazakhstan that are engaged in scientific research in this field. Among them are Nazarbayev University, Kazakh National Research Technical University named after K.I. Satpayev, Eurasian National University named after L.N. Gumilyov, Institute of Coal Chemistry and Technology LLP, D.V. Sokolsky Institute of Fuel, Catalysis, and Electrochemistry JSC, as well as the Kazakh-British Technical University (KMG Engineering 2021).

In addition to the above, KazMunayGas has established collaborative agreements in the field of hydrogen energy with renowned companies like Eni, AirLiquide, and Linde. These partnerships aim to jointly develop and implement innovative hydrogen energy technologies in Kazakhstan, while also contributing to the country's hydrogen infrastructure development and environmental sustainability (CHEManager 2021).

In June 2022, with the support of KAZAKH INVEST, several companies from Germany, Italy, Spain, and Kazakhstan signed an agreement to establish the Green Hydrogen Alliance in Kazakhstan. Participants in this initiative include Linde (Germany), Svevind Energy GmbH (Germany), Roedl & Partners (Germany), Qazaq Gaz (Kazakhstan), Atasu Group (Kazakhstan), Green Spark LTD (Italy), Green Finance Center – AIFC (Kazakhstan), GCA Partners (Kazakhstan), Ajusa Hydrogen Technologies (Spain), and other international companies from the European Union (KAZAKH INVEST 2022).

In October 2021, Kazakh Invest and the Swedish company Svevind signed a roadmap for the development of a 30 GW green hydrogen production project in the West Kazakhstan region, specifically in the Mangystau region. Additionally, in August 2022, ACWA Power, a Saudi Arabian company, expressed their intent to explore similar projects (KAZAKH INVEST 2022).

In October 2021, as part of its Environmental Strategy, the mining and metallurgical company ERG announced that it is investigating the potential of substituting fuel oil and diesel with hydrogen at its facilities (Smagulova et al. 2023).

5.2. Promising and possible programs

The Kazakhstan government's commitment to achieving carbon neutrality by 2060 forms the basis for the development of a hydrogen economy in the country and signifies a significant dedication (Chen et al. 2022). To facilitate large-scale production of low-carbon hydrogen domestically, it is crucial to establish sources of low-carbon electricity, such as renewable energy sources and nuclear power plants, while also employing carbon capture and storage (CCUS) technology for hydrogen production using locally extracted natural gas. Pilot projects utilizing hydrogen derived from greenhouse gas emissions, such as those from existing oil refineries, can be implemented to refine technological processes until low-carbon hydrogen production becomes viable (Chen et al. 2022).

The initial utilization of hydrogen within Kazakhstan can commence with pilot projects in the transportation sector, particularly considering that companies like KazMunayGas and ERG are already exploring such possibilities (Howie et al. 2022). This may involve deploying pilot hydrogen-powered buses and gradually developing hydrogen refueling infrastructure near hydrogen production facilities, including oil refineries. These steps represent the initial phases of establishing a hydrogen economy in the country and can serve as a model for other nations (Zholdayakova et al. 2022).

Establishing goals for carbon neutrality and implementing various energy measures in the transportation sector, such as prohibiting internal combustion engines, implementing emission regulations, providing incentives like preferential parking and priority passage, subsidies, and tax benefits, can create a regulatory environment favorable to such initiatives (Zhang et al. 2021). As infrastructure expands and technology costs decrease, the utilization of low-carbon hydrogen in industries like oil refining and metallurgy can also be explored (Zhang et al. 2021).

Further research is necessary to investigate the feasibility of transporting hydrogen through existing gas infrastructure, taking into account the experiences of gas companies in Europe and the United States, such as Shell, Gasunie, Snam and others (Noussan et al. 2020).

To enable large-scale hydrogen exports through existing infrastructure, including pipelines, collaboration with gas companies in importing countries like Russia and China would be required (Panchenko et al. 2023). At present, Russia's Gazprom has no intentions of utilizing gas infrastructure for hydrogen transportation. Among Kazakhstan's immediate neighboring countries, only China, Russia, and Uzbekistan are developing strategies for hydrogen utilization, but there is currently no explicit demand for hydrogen imports from these nations (Yakubson 2020).

It is crucial to consider the diverse potential pathways outlined in Kazakhstan's national hydrogen strategy for the development of a hydrogen economy. In this process, international organizations can provide methodological support.

6. Problems and prospects of hydrogen energy development in Kazakhstan

Hydrogen energy has the potential to become an important component of Kazakhstan's energy system. As discussed in this review, it can help reduce dependence on fossil fuels, reduce greenhouse gas emissions, and improve the country's energy security. However, there are currently some problems and challenges in Kazakhstan that hinder the full development of hydrogen energy. Below in this section, we clearly define the problems and prospects for the development of hydrogen power in Kazakhstan.

6.1. Problems of development of hydrogen energy

The development of hydrogen energy in Kazakhstan faces several challenges that need to be addressed for successful implementation. Here are some of the key problems:

1. Infrastructure: One of the major hurdles is the lack of a well-developed hydrogen infrastructure. Building hydrogen production, storage and distribution facilities requires significant investments in terms of capital and technical expertise. Currently, Kazakhstan's infrastructure is primarily focused on conventional fossil fuels, making the transition to hydrogen more challenging.

2. Cost: Hydrogen production, especially through methods like electrolysis, can be expensive compared to the costs associated with traditional energy sources. The high cost of hydrogen production, storage and transportation infrastructure can hinder its widespread adoption, especially in the early stages of development.

3. Renewable Energy Integration: Hydrogen is often produced through electrolysis, which requires electricity. Integrating renewable energy sources, such as wind or solar power, into the electricity grid is crucial for producing green hydrogen. However, Kazakhstan faces challenges in terms of grid stability, intermittent power generation, and geographic suitability for renewables, which can impact the availability and cost of clean energy for hydrogen production.

4. Technological Maturity: While hydrogen energy has great potential, some of the necessary technologies are still in the early stages of development and not yet commercially mature. Advancements in hydrogen production, storage and transportation technologies are needed to make them more efficient, cost-effective and reliable.

5. International Cooperation: The development of a hydrogen economy often requires international collaboration, including technology transfer, investment, and market development. Establishing partnerships and collaborations with countries that have advanced expertise in hydrogen technologies can accelerate the development process. However, international cooperation may face geopolitical, regulatory and logistical challenges that need to be addressed.

6. Market Demand and Incentives: The demand for hydrogen as an energy source is currently limited, and developing a sustainable market for hydrogen is crucial for its long-term viability. Encouraging industries to adopt hydrogen as an alternative fuel and creating favorable policies, such as financial incentives and regulations that promote its use, can help drive market demand.

7. Safety Considerations: Hydrogen is highly flammable and requires specific safety measures for production, storage and transportation. Developing robust safety protocols, regulations and standards is crucial to address any safety concerns associated with hydrogen infrastructure and build public confidence in its usage.

Addressing these challenges will require coordinated efforts from the government, industry stakeholders and research institutions to develop a comprehensive strategy for hydrogen energy development in Kazakhstan. By investing in research and development, creating supportive policies, and fostering international partnerships, Kazakhstan can overcome these obstacles and unlock the potential of hydrogen as a clean energy source.

6.2. Prospects for the development of hydrogen energy

The development of hydrogen energy in Kazakhstan holds significant prospects due to the country's abundant natural resources and its strategic geographic location. Here are some key points highlighting the prospects for hydrogen energy in Kazakhstan:

1. Abundant Renewable Energy Sources: Kazakhstan has substantial renewable energy potential, particularly in wind and solar power. These renewable sources can be utilized to produce green hydrogen through electrolysis, making it an attractive option for clean energy production.

2. Vast Hydrocarbon Reserves: Kazakhstan possesses significant hydrocarbon reserves, including natural gas, coal and oil. These resources can be used to produce blue hydrogen through steam methane reforming or coal gasification with carbon capture and storage (CCS) technologies. Blue hydrogen can serve as a transitional fuel on the path to decarbonization.

3. Strategic Geographic Location: Kazakhstan occupies a strategic position between Europe and Asia, making it an ideal hub for hydrogen production, transportation and export. It can potentially supply hydrogen to neighboring countries, such as China, Russia and European nations, thereby bolstering its economy through energy exports.

4. International Collaboration: Kazakhstan is actively engaged in international collaborations and partnerships to promote the development of hydrogen energy. The country has joined initiatives like the Hydrogen Initiative of the Clean Energy Ministerial and the Hydrogen Energy Ministerial Meeting, demonstrating its commitment to fostering hydrogen energy solutions.

5. Government Support and Policies: The Kazakhstani government has shown strong support for the development of hydrogen energy. It has implemented various policies and initiatives to encourage investment, research and development in the sector. This support includes regulatory frameworks, financial incentives and the establishment of innovation clusters and research centers.

6. Diversification of Energy Portfolio: Developing hydrogen energy can help Kazakhstan diversify its energy portfolio and reduce dependence on fossil fuels. It aligns with global efforts to mitigate climate change, promote sustainable development and transition to a low-carbon economy.

7. Industrial Applications and Export Potential: Hydrogen can be used in various industries, including transportation, power generation, heating and chemical production. Kazakhstan's hydrogen production capabilities can support the country's industrial sectors, create new job opportunities and potentially drive export revenue.

Despite the above points, it is worth noting that the successful development of hydrogen energy in Kazakhstan will require overcoming challenges such as high initial investment costs, establishing infrastructure for hydrogen production, storage and transportation, and ensuring the long-term sustainability of hydrogen supply chains.

Overall, with its favorable resources, geographic location and government support, Kazakhstan has promising prospects for the development of hydrogen energy as a key component of its sustainable energy future.

As a final result of this review, we came to the conclusion that for the successful implementation of the development of hydrogen energy in Kazakhstan, a national roadmap of the country is needed. Therefore, we have developed a roadmap for the development of hydrogen energy in Kazakhstan until 2040 with various technologies (Fig. 20).

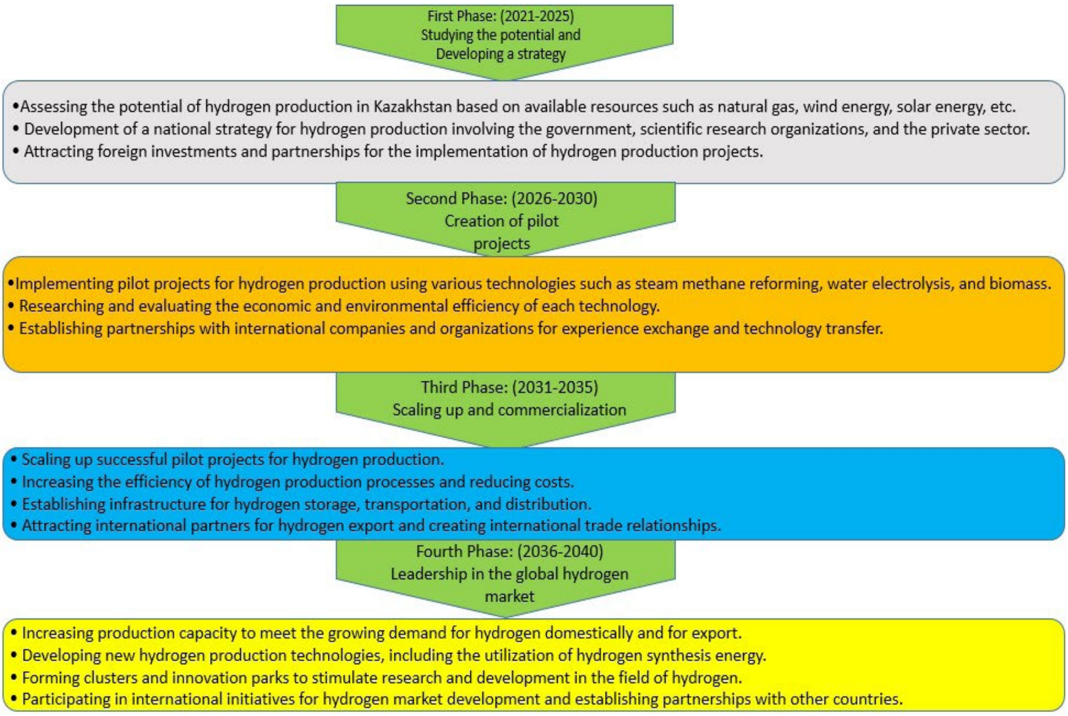

Fig. 20. Roadmap for the development of hydrogen energy in Kazakhstan by 2040

Rys. 20. Mapa drogowa rozwoju energetyki wodorowej w Kazachstanie do 2040 roku

Conclusions

In the development of hydrogen energy in Kazakhstan, significant prospects and opportunities lie for the country. In this regard, the government of Kazakhstan faces the immense task of developing a national strategy for the active advancement of hydrogen energy in the country. Implementing projects, establishing partnerships with international investors, and creating the necessary infrastructure will enable Kazakhstan to occupy a key position in the global hydrogen energy sector and achieve the set goals in terms of environmental sustainability and energy security.

Below are the main conclusions drawn from this review:

1. Kazakhstan, a country rich in energy resources, is a significant regional exporter of coal, uranium, oil and gas, with extraction rates on the rise. However, the dominance of coal in the power generation and heat supply sectors has led to a rapid increase in greenhouse gas emissions.

2. Despite the above point, Kazakhstan has set an ambitious target to achieve carbon neutrality by 2060. The country has adopted its first long-term strategic documents and is developing additional measures to transform its energy sector, with a particular focus on the extensive development of renewable energy sources (RES). Since 2018, Kazakhstan has reintroduced a carbon dioxide (CO_2) emissions trading system, and multiple RES projects involving investors from twelve countries have been selected through auctions.

3. Kazakhstan possesses significant potential in the field of renewable energy sources (RES) due to its vast territory. The strategic documents outline goals to substantially increase electricity production from RES by 2030–2050. As a result, the production of green hydrogen using electricity from RES emerges as a promising avenue in Kazakhstan. Furthermore, there is considerable potential for nuclear energy, which is being explored, as well as opportunities to boost natural gas production and investigate the construction of the country's inaugural nuclear power plant.

4. Kazakhstan is presently implementing notable large-scale projects for green hydrogen production. One such project is being developed by SVEVIND AB, which plans to construct wind and solar power plants with a combined capacity of 30 GW in the Mangystau region. The generated electricity will be utilized to produce up to two million tons of hydrogen annually. This initiative exemplifies Kazakhstan's commitment to fostering a green hydrogen economy and participating in global endeavors to combat climate change.

5. The availability of diverse resources for low-carbon hydrogen production in Kazakhstan presents extensive prospects for generating a synergistic effect and accelerating the development of the hydrogen economy within the country. This potential enables the realization of large-scale hydrogen production benefits, leading to enhanced resource utilization efficiency and improved economic effectiveness. Such an approach allows Kazakhstan to maximize its advantages and expedite the transition towards a low-carbon economy through hydrogen utilization.

6. By assessing the available resources and energy sources for hydrogen production, Kazakhstan's potential for low-carbon hydrogen production is estimated to range from 169,000 to 2,624,000 tons per year. This estimation considers the utilization of electrolysis with renewable energy sources (RES) and methane reforming with carbon capture and storage (CCS) technology. The range provides an evaluation of various scenarios and options for the development of the hydrogen economy in Kazakhstan, considering different resources and technologies.

7. Among the various options for low-carbon hydrogen production in Kazakhstan, methane reforming combined with carbon capture and utilization/storage (CCUS) technology appears to be the most cost-effective choice.

8. The gas transportation infrastructure in Kazakhstan, overseen by the Qazaq Gaz company, plays a crucial role in connecting the country's gas-producing regions with gas-consuming sectors and facilitating gas transit from Uzbekistan and Turkmenistan for export to Russia and China. In the short term, Kazakhstan may prioritize increasing domestic gas consumption in

industries, energy and households and halt gas exports. However, utilizing the gas transportation infrastructure for hydrogen transportation will require further research and the involvement of all stakeholders. Since gas and hydrogen possess different physical and chemical properties, it is necessary to explore the potential for adapting and modifying the existing infrastructure to ensure safe and efficient hydrogen transportation. This entails analyzing technical compatibility, safety measures, efficiency, and the economic feasibility of employing gas pipelines and other components of the gas transportation system for hydrogen. Collaborative research involving all stakeholders will help assess the potential and develop recommendations for utilizing the gas transportation infrastructure for hydrogen transportation in Kazakhstan, optimizing the use of existing resources and infrastructure for the development of a hydrogen economy in the country.

9. While there are currently no realized pilot projects for low-carbon hydrogen production in Kazakhstan, companies such as KazMunayGas, ERG, Qazaq Gaz, Kazakh Invest, and others have already incorporated this direction into their strategies and established partnerships with international firms. This demonstrates Kazakhstan's interest in developing low-carbon hydrogen and its potential for environmental sustainability and energy security. One potential avenue to commence the use of low-carbon hydrogen within the Kazakh economy is its application in the transportation sector, where hydrogen fuel cells and hydrogen refueling stations can play a significant role in reducing greenhouse gas emissions. Additionally, the hydrocarbon processing and metallurgy sectors could also become potential consumers of low-carbon hydrogen in Kazakhstan. With the increasing interest and strategic focus from companies and the government, plans and projects aimed at implementing low-carbon hydrogen in various sectors of Kazakhstan's economy are likely to be developed. This will contribute to the development of a low-carbon energy system and support the achievement of goals related to sustainable development and environmental responsibility.

10. Developing a national hydrogen strategy can play a vital role in defining the prospects and development plans for the hydrogen economy in Kazakhstan. International organizations can provide essential support in this process by offering methodological guidance, expert knowledge and experience. Organizations such as the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA) and others can offer recommendations and best practices in the field of the hydrogen economy and assist with potential analysis, the development of strategic plans and regulation in this sector. Additionally, international financial institutions and organizations like the World Bank, the European Bank for Reconstruction and Development (EBRD) and others can provide financial support for hydrogen economy projects and infrastructure implementation. Collaborating with international organizations will allow Kazakhstan to benefit from global experience, expertise and resources, as well as establish partnerships with other countries that are already advancing hydrogen technologies. This will contribute to the development of effective strategies tailored to Kazakhstan's national conditions and capabilities, facilitating the successful implementation of the hydrogen economy in the country.

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References

Abdildin et al. 2021 – Abdildin, Y.G., Nurkenov, S.A. and Kerimray, A. 2021. Analysis of green technology development in Kazakhstan. *International Journal of Energy Economics and Policy* 11(3), pp. 269–279, DOI: 10.32479/ijeep.10897.

Abuov et al. 2020 – Abuov, Y., Seisenbayev, N. and Lee, W. 2020 – CO_2 storage potential in sedimentary basins of Kazakhstan. *International Journal of Greenhouse Gas Control* 103, DOI: 10.1016/j.ijggc.2020.103186.

Adilbektegi et al. 2019 – Adilbektegi, G., Mustafayev, J.S., Uvatayeva, T.K., Dulatbekova, Z.N. and Mosiej, J. 2019. A new approach to the evaluation of bioclimatic potential of landscapes on the example of Northern Kazakhstan. News of the national academy of sciences of the republic of Kazakhstan, *Series of geology and technical sciences* 5(437). DOI: 10.32014/2019.2518-170X.121.

Adilet zan 2022. On the Approval of the Concept for the Development of the Gas Sector of the Republic of Kazakhstan until 2030. [Online] https://adilet.zan.kz/rus/docs/P1400001275 [Accessed: 2023-12-15] (*in Russian*).

Adilet zan 2012. Strategy «Kazakhstan-2050»: a new political course of an established state. [Online] https://adilet.zan.kz/rus/docs/K1200002050 [Accessed: 2012-12-14] (*in Russian*).

Agumbayeva, A. 2016. Low carbon development of Kazakhstans energy sector for sustainable economic growth. *Turan University Bulletin* 2016(4), pp. 85–92. [Online] https://elibrary.ru/item.asp?id=27697512 [Accessed: 2024-02-15] (*in Russian*).

Ahmad et al. 2017 – Ahmad, S., Nadeem, A., Akhanova, G., Houghton, T. and Muhammad-Sukki, F. 2017. Multi-criteria evaluation of renewable and nuclear resources for electricity generation in Kazakhstan. *Energy* 141, pp. 1880–1891, DOI: 10.1016/j.energy.2017.11.102.

Aizhana et.al 2022 – Aizhana, M., Maira, D., Assel, I. and Erkeb ulan, B. 2022. Improving marketing approaches to the energy sector of Kazakhstan for decarbonization. *International Journal of Energy Economics and Policy* 12(3), pp. 410–417, DOI: 10.32479/ijeep.12997.

Albatayneh et al. 2023 – Albatayneh, A., Juaidi, A., Jaradat, M. and Manzano-Agugliaro, F. 2023. Future of Electric and Hydrogen Cars and Trucks: An Overview. *Energies* 16(7), DOI: 10.3390/en16073230.

Alimbaev et. al 2019 – Alimbaev, T.A., Mazhitova, Z.S., Omarova, B.K. and Nurkina, Z.B. 2019. Environmental problems in the Kazakhstan coal industry and their solutions. [In:] *IOP Conference Series: Materials Science and Engineering* 663, DOI: 10.1088/1757-899X/663/1/012041.

Alptekin, F.M. and Celiktas, M.S. 2022. Review on Catalytic Biomass Gasification for Hydrogen Production as a Sustainable Energy Form and Social, Technological, Economic, Environmental, and Political Analysis of Catalysts. *ACS omega* 7(29), pp. 24918–24941, DOI: 10.1021/acsomega.2c01538

Antonini et al. 2020 – Antonini, C., Treyer, K., Streb, A., van der Spek, M., Bauer, C. and Mazzotti, M. 2020. Hydrogen production from natural gas and biomethane with carbon capture and storage–A techno-environmental analysis. *Sustainable Energy & Fuels* 4(6) pp. 2967–2986, DOI: 10.1039/D0SE00222D.

Arslan, M. 2014. The significance of shifting Capital of Kazakstan from Almaty to Astana: An Evalution on the basis of geopolitical and demographic developments. *Procedia-Social and Behavioral Sciences* 120, pp. 98–109, DOI: 10.1016/j.sbspro.2014.02.086.

Askarova, et al. 2022 – Askarova, A., Georgiev, A., Bolegenova, S., Beketayeva, M., Maximov, V. and Bolegenova, S. 2022. Computational modeling of pollutants in furnaces of pulverized coal boilers of the republic of Kazakhstan. *Energy* 258, DOI: 10.1016/j.energy.2022.124826.

Association of Practicing Ecologists 2018. Concept for the transition to a green economy of the Republic of Kazakhstan. [Online] https://ecounion.kz/?p=686; [Accessed: 2018-11-20].

Aydin, K. and Kenanoğlu, R. 2018. Effects of hydrogenation of fossil fuels with hydrogen and hydroxy gas on performance and emissions of internal combustion engines. *International Journal of Hydrogen Energy* 43(30), pp. 14047–14058, DOI: 10.1016/j.ijhydene.2018.04.026.

Azimov, U. and Avezova, N. 2022. Sustainable small-scale hydropower solutions in Central Asian countries for local and cross-border energy/water supply. *Renewable and Sustainable Energy Reviews* 167, DOI: 10.1016/j.rser.2022.112726.

Barrett et al. 2017 – Barrett, T., Feola, G., Khusnitdinova, M. and Krylova, V. 2017. Adapting agricultural water use to climate change in a post-Soviet context: Challenges and opportunities in Southeast Kazakhstan. *Human Ecology* 45, pp. 747–762, DOI: 10.1007/s10745-017-9947-9.

Bealessio et al. 2021 – Bealessio, B.A., Alonso, N.A., Mendes, N.J., Sande, A.V. and Hascakir, B. 2021. A review of enhanced oil recovery (EOR) methods applied in Kazakhstan. *Petroleum* 7(1), pp. 1–9, DOI: 10.1016/j.petlm.2020.03.003.

Bespalyy, S. 2021. Kazakhstan: Assessment of renewable energy support and a green economy. *Journal of Environmental Management and Tourism (JEMT)* 12(3), pp. 631–641, DOI: 10.14505//jemt.v12.3(51).03.

Bhavsar et al. 2023 – Bhavsar, A., Hingar, D., Ostwal, S., Thakkar, I., Jadeja, S. and Shah, M. 2023. The current scope and stand of carbon capture storage and utilization ~ A comprehensive review. *Case Studies in Chemical and Environmental Engineering* 8, DOI: 10.1016/j.cscee.2023.100368.

Bogdanov et al. 2019 – Bogdanov, D., Toktarova, A. and Breyer, C. 2019. Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan. *Applied Energy* 253, DOI: 10.1016/j.apenergy.2019.113606.

Boute, A. 2020. Regulatory stability and renewable energy investment: The case of Kazakhstan. *Renewable and Sustainable Energy Reviews* 121, DOI: 10.1016/j.rser.2019.109673.

Brändle et al. 2021 – Brändle, G., Schönfisch, M. and Schulte, S. Estimating long-term global supply costs for low-carbon hydrogen. *Applied Energy* 302, DOI: 10.1016/j.apenergy.2021.117481.

Capital 2023. Path to Carbon Neutrality: The Role of the Banking Sector in Decarbonization Agenda Implementation. [Online] https://kapital.kz/finance/113084/put-uglerodnoy-neytral-nosti.html; [Accessed: 2023-02-20].

Ceran, B. 2018. A comparative analysis of energy storage technologies. *Polityka Energetyczna – Energy Policy Journal* 21(3), pp. 97–110, DOI: 10.24425/124498.

Chanchetti et.al 2020 – Chanchetti, L.F., Leiva, D.R., de Faria, L.I. and Ishikawa, T.T. 2020. A scientometric review of research in hydrogen storage materials. *International Journal of Hydrogen Energy* 45(8), pp. 5356–5366, DOI: 10.1016/j.ijhydene.2019.06.093.

Chang et al. 2011 – Chang, A.C., Chang, H.F., Lin, F.J., Lin, K.H. and Chen, C.H. 2011. Biomass gasification for hydrogen production. *International Journal of Hydrogen Energy* 36(21), pp. 14252–14260, DOI: 10.1016/j.ijhydene.2011.05.105.

CHEManager 2021. Linde and KazMunayGas in Clean Energy Pact. [Online] https://www.chemanager-online.com/en/news/linde-and-kazmunaygas-clean-energy-pact [Accessed: 2021-11-26].

Chen et al. 2022 – Chen, S., Liu, J., Zhang, Q., Teng, F. and McLellan, B.C. 2022. A critical review on deployment planning and risk analysis of carbon capture, utilization, and storage (CCUS) toward carbon neutrality. *Renewable and Sustainable Energy Reviews* 167, DOI: 10.1016/j.rser.2022.112537.

Cheng et al. 2021 – Cheng, W.H., De La Calle, A., Atwater, H.A., Stechel, E.B. and Xiang, C. 2021. Hydrogen from sunlight and water: A side-by-side comparison between photoelectrochemical and solar thermochemical water-splitting. *ACS Energy Letters* 6(9), pp. 3096–3113, DOI: 10.1021/acsenergylett.1c00758.

Coal industry of Kazakhstan 2022. The coal industry of Kazakhstan. [Online] https://factories.kz/news/ugolnaya-promyshlennost-kazakhstana; [Accessed: 2022-02-01].

Collet et al. 2022 – Collet, A., Regnault, O., Ozhogin, A., Imantayeva, A. and Garnier, L. 2022. Three-dimensional reactive transport simulation of Uranium in situ recovery: Large-scale well field applications in Shu Saryssu Bassin, Tortkuduk deposit (Kazakhstan). *Hydrometallurgy* 211, DOI: 10.1016/j.hydromet.2022.105873.

Danenova et al. 2022 – Danenova, S., Abuov, Y., Tleubergenova, A. and Lee, W. 2022. Preliminary assessment of the green hydrogen production potential in Kazakhstan. [In:] *23rd World Hydrogen Energy Conference: Bridging Continents by H2, WHEC 2022*, pp. 1017–1019. International Association for Hydrogen Energy, IAHE.

Dawood et al. 2019 – Dawood, F., Anda, M. and Shafiullah, G.M. 2019. Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy* 45(7), pp. 3847–3869, DOI: 10.1016/j.ijhydene.2019.12.059.

Development plan of the hydropower industry of the Republic of Kazakhstan for 2020–2030, 2020. Development plan of the hydropower industry of the Republic of Kazakhstan for 2020–2030. [Online] https://www.gov.kz/uploads/2021/9/1/7883c3588214390e9cc3f3a7723c7ef6_original.3531983.pdf; [Accessed: 2020-12-16].

Development Strategy «Kazakhstan-2050» 2016. (*Strategiya razvitiya «Kazakhstan-2050»*). [Online] https://greenbridgework.kaznu.kz/?p=1950 [Accessed: 2016-02-29] (*in Russian*).

Doctrine (strategy) of achieving carbon neutrality of the Republic of Kazakhstan until 2060, 2021. (*Doktrina (strategiya) dostizheniya uglerodnoy neytral'nosti Respubliki Kazakhstan do 2060 goda*). [Online] https://legalacts.egov.kz/npa/view?id=11488215 [Accessed: 2021-09-14] (*in Russian*).

Ergazieva et al. 2020 – Ergazieva, G.E., Telbaeva, M.M., Dosumov, K. and Niyazbaeva, A.I. 2020. Promising methods for hydrogen production. *Combustion and plasma chemistry* 18(1), pp. 23–28. [Online] https://www.elibrary.ru/item.asp?id=43136731 [Accessed: 2024-03-22].

Falcone et al. 2021 – Falcone, P.M., Hiete, M. and Sapio, A. 2021. Hydrogen economy and sustainable development goals: Review and policy insights. *Current Opinion in Green and Sustainable Chemistry* 31, DOI: 10.1016/j.cogsc.2021.100506.

Forbes 2021. The energy process in Kazakhstan. [Online] https://forbes.kz/process/energetics/v_kazahstane__izbyitok_gaza_no_vostok_stranyi_gazifitsiruyut_za_schet_rossii/ [Accessed: 2023-12-06].

Forbes 2022. How many uranium reserves are left in Kazakhstan. [Online] https://forbes.kz/process/resources/skolko_zapasov_urana_ostalos_v_kazahstane [Accessed: 2022-11-21].

Fugiel, A. and Burchart-Korol, D. 2016. Identification of environmental problems using Life Cycle Assessment approach on the coal gasification example. *Polityka Energetyczna – Energy Policy Journal* 19(4), pp. 51–62.

Golovina et al. 2021 – Golovina, E., Pasternak, S., Tsiglianu, P. and Tselischev, N. 2021. Sustainable management of transboundary groundwater resources: Past and future. *Sustainability* 13(21), DOI: 10.3390/su132112102.

Gray et al. 2021 – Gray, N., McDonagh, S., O'Shea, R., Smyth, B. and Murphy, J.D. 2021. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy* 1, DOI: 10.1016/j.adapen.2021.100008.

Harutyunyan, A.A. 2022. China-Kazakhstan: Cooperation within The Belt and Road and Nurly Zhol. *Asian Journal of Middle Eastern and Islamic Studies* 16(3), pp. 281–297, DOI: 10.1080/25765949.2022.2128135.

Hosseini, S.E. and Wahid, M.A. 2020. Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy. *International Journal of Energy Research* 44(6), pp. 4110–4131, DOI: 10.1002/er.4930.

Hosseini, S.E. 2022. Hydrogen has found its way to become the fuel of the future. *Future Energy* 1(2), pp. 11–12, DOI: 10.55670/fpll.fuen.1.3.2.

How will «green» hydrogen be produced in Kazakhstan 2022. (*Kak v Kazakhstane budut proizvodit' „zelenyy" vodorod?*) [Online] https://el.kz/ru/kak_v_kazakhstane_budut_proizvodit_-zelenyy-_vodorod_44042/ [Accessed: 2022-07-08] (*in Russian*).

Howarth, R.W. and Jacobson, M.Z. 2021. How green is blue hydrogen? *Energy Science & Engineering* 9(10), pp. 1676–1687, DOI: 10.1002/ese3.956.

Howie, P. and Atakhanova, Z. 2022. Assessing initial conditions and ETS outcomes in a fossil-fuel dependent economy. *Energy Strategy Reviews* 40, DOI: 10.1016/j.esr.2022.100818.

Ishaq et al. 2022 – Ishaq, H., Dincer, I. and Crawford, C. 2022. A review on hydrogen production and utilization: Challenges and opportunities. *International Journal of Hydrogen Energy* 47(62), pp. 26238–26264, DOI: 10.1016/j.ijhydene.2021.11.149.

Issanova et al. 2018 – Issanova, G., Jilili, R., Abuduwaili, J., Kaldybayev, A., Saparov, G. and Yongxiao, G. 2018. Water availability and state of water resources within water-economic basins in Kazakhstan. *Paddy and water environment* 16, pp. 183–191, DOI: 10.1007/s10333-018-0630-6.

Jianzhong et al. 2018 – Jianzhong, X.U., Assenova, A. and Erokhin, V. 2018. Renewable energy and sustainable development in a resource-abundant country: Challenges of wind power generation in Kazakhstan. *Sustainability* 10(9), DOI: 10.3390/su10093315.

JSC «KEGOC» Annual Refort 2021. (*JSC «KEGOC» Godovoy Otchet* 2021). [Online] https://www.kegoc.kz/upload/iblock/063/c4rkeuhitwv3v569zkm0mudm5i68g1xz.pdf [Accessed: 2021-11-03] (*in Russian*).

Kadirbayeva, Y.E. and Bukpina, A.Y. 2016. The relevance and significance of the theme of the international specialized exhibition expo-2017 «future energy». *Archivist* 2(4(8)), pp. 5–7. [Online] https://cyberleninka.ru/article/n/aktualnost-i-znachimost [Accessed: 2024-02-15] (*in Russian*).

Kaiser, M.J. and Pulsipher, A.G. 2007. A review of the oil and gas sector in Kazakhstan. *Energy Policy* 35(2), pp. 1300–1314, DOI: 10.1016/j.enpol.2006.03.020.

Kalyuzhnova, Y. and Patterson, K. 2016. Kazakhstan: long-term economic growth and the role of the oil sector. *Comparative Economic Studies* 58, pp. 93–118, DOI: 10.1057/ces.2015.31.

Kanapiyanova, Z. 2019. History of the energy sector development and Kazakhstan's energy potential. *Eurasian Research Journal* 1(2), pp. 25–38. [Online] https://dergipark.org.tr/en/pub/erj/issue/47886/605473 [Accessed: 2023-12-05].

Karaca et al. 2020 – Karaca, A.E., Dincer, I. and Gu, J. 2020. Life cycle assessment study on nuclear based sustainable hydrogen production options. *International Journal of Hydrogen Energy* 45(41), pp. 22148–22159, DOI: 10.1016/j.ijhydene.2020.06.030.

Karatayev et al. 2016 – Karatayev, M., Hall, S., Kalyuzhnova, Y. and Clarke, M.L. 2016. Renewable energy technology uptake in Kazakhstan: Policy drivers and barriers in a transitional economy. *Renewable and Sustainable Energy Reviews* 66, pp. 120–136, DOI: 10.1016/j.rser.2016.07.057.

Karatayev, M. and Hall, S. 2017. Integration of wind and solar power in Kazakhstan: Incentives and barriers. [In:] *Sustainable Energy in Kazakhstan*, 1st Edition, pp. 65–89, Routledge.

Karatayev et al. 2017 – Karatayev, M., Rivotti, P., Mourão, Z.S., Konadu, D.D., Shah, N. and Clarke, M. 2017. The water-energy-food nexus in Kazakhstan: challenges and opportunities. *Energy Procedia* 125, pp. 63–70, DOI: 10.1016/j.egypro.2017.08.064.

Karpiński, M. 2012. System of Intervention Stocks of Crude Oil and Fuels within the International Energy Agency. *Polityka Energetyczna – Energy Policy Journal* 15(2), pp. 57–69.

Kazakh Invest 2015. Kazakhstan will provide the European Union with green hydrogen. [Online] https://invest.gov.kz/ru/media-center/press-releases/kazakhstan-obespechit-evrosoyuz-zelenym-vodorodom/; [Accessed: 2015-08-26].

KAZAKH INVEST 2022a. Kazakhstan will provide the European Union with green hydrogen (*Kazakhstan obespechit Yevrosoyuz zelenym vodorodom*). [Online] https://invest.gov.kz/ru/media-center/press-releases/kazakhstan-obespechit-evrosoyuz-zelenym-vodorodom/; [Accessed: 2022-10-27] (*in Russian*).

KAZAKH INVEST 2022b. The Green Hydrogen Alliance with the participation of transnational companies was created in Kazakhstan (*V Kazakhstane sozdan Al'yans Zelenogo Vodoroda s uchastiyem transnatsional'nykh kompaniy*). [Online] https://invest.gov.kz/ru/media-center/press-releases/green-hydrogen-alliance-established-in-kazakhstan-with-the-participation-of-9-transnational-companie/; [Accessed: 2022-06-29] (*in Russian*).

KAZAKH INVEST 2023. The Green Hydrogen project is special in terms of the future – Kazakh invest (*Proyekt «Zelenyy vodorod» osobennyy s tochki zreniya zadela na budushcheye – Kazakh invest*). [Online] https://www.inform.kz/ru/proekt-zelenyy-vodorod-osobennyy-s-tochki-zreniya-zadela-na-buduschee-kazakh-invest_a4061762; [Accessed: 2023-04-28] (*in Russian*).

Kazakhstan Programs and Activities 2020. Kazakhstan Programs and Activities: Uranium Mining and Management. [Online] https://www.afcone.org/wp-content/uploads/2020/12/07-Timur-Zhantikin-DG-Kazakhstan-Programs-Activities-Uranium.pdf [Accessed: 2020-09-10].

Kazakhstan Truth 2013. Solar alternative (*Kazakhstanskaya pravda 2013. Solnechnaya al'ternativa*). [Online] https://kazpravda.kz/n/solnechnaya-alternativa/ [Accessed: 2013-11-27] (*in Russian*).

Kazakhstan Truth 2017. Investment in the future (*Kazakhstanskaya pravda 2017. Investitsii v budushcheye*). [Online] https://kazpravda.kz/n/investitsii-v-budushchee-ei/ [Accessed: 2017-06-23] (*in Russian*).

Kazakhstan's National Energy Report 2021. Kazakhstan's National Energy Report 2021. [Online] https://www.kazenergy.com/upload/document/operation/forum/2021_English_presentation_IHS_Markit.pdf [Accessed: 2021-10-06].

Kerimray et al. 2018 – Kerimray, A., Suleimenov, B., De Miglio R., Rojas-Solórzano, L., Torkmahalleh, M.A. and Gallachóir, B.P. 2018. Investigating the energy transition to a coal free residential sector in Kazakhstan using a regionally disaggregated energy systems model. *Journal of Cleaner Production* 196, pp. 1532–1548, DOI: 10.1016/j.jclepro.2018.06.158.

Kerimray et al. 2018 – Kerimray, A., Suleimenov, B., De Miglio, R., Rojas-Solórzano, L. and Ó Gallachóir. B. 2018. Long-term climate change mitigation in Kazakhstan in a post Paris agreement context. *Limiting Global Warming to Well Below 2°C: Energy System Modelling and Policy Development*, pp. 297–314, DOI: 10.1007/978-3-319-74424-7_18.

Khan et al. 2021 – Khan, M.H., Daiyan, R., Neal, P., Haque, N., MacGill, I. and Amal, R. 2021. A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation. *International Journal of Hydrogen Energy* 46(44), pp. 22685–22706, DOI: 10.1016/j.ijhydene.2021.04.104.

Khomamatovich, N.O. and Imidjanovich, M.D. 2022. Hydrogen energy development trends in foreign countries. *Galaxy International Interdisciplinary Research Journal* 10(12), pp. 2012–2020. [Online] https://giirj.com/index.php/giirj/article/view/4258 [Accessed: 2023-11-23].

Klinovitskaya et al. 2019 – Klinovitskaya, I., Kalygulov, D., Plotnikov, S. and Lay, P. 2019. Increasing the efficiency of photovoltaic cells based on Kazakhstan silicon. *Bulgarian Chemical Communications* 51, pp. 41–48. [Online] http://www.bcc.bas.bg/bcc_volumes/Volume_51_Special_F_2019 [Accessed: 2023-11-10].

KMG Engineering 2021. KMG Engineering has launched the Hydrogen Energy Competence Center. [Online] https://www.kmge.kz/%D1%80%D0%B0%D0%B7%D [Accessed: 2023-11-10] (*in Russian*).

KMG Engineering 2022. Development of hydrogen energy is a priority for KMG and KMGI. [Online] https://www.kmge.kz/%D0%B2-%D0%BA%D0%BC%D0% [Accessed: 2023-11-10] (*in Russian*).

Konopelko, A. 2018. Eurasian Economic Union: a challenge for EU policy towards Kazakhstan. *Asia Europe Journal* 16(1), pp. 1–7, DOI: 10.1007/s10308-017-0480-7.

Koshim et al. 2018 – Koshim, A., Karatayev, M., Clarke, M.L. and Nock, W. 2018. Spatial assessment of the distribution and potential of bioenergy resources in Kazakhstan. *Advances in Geosciences* 45, pp. 217–225, DOI: 10.5194/adgeo-45-217-2018.

Kossalbayev et al. 2022 – Kossalbayev, B.D., Kakimova, A.B., Bolatkhan, K., Zayadan, B.K., Sandybayeva, S.K., Bozieva, A.M., Sadvakasova, A.K., Alwasel, S. and Allakhverdiev, S.I. 2022. Biohydrogen production by novel cyanobacterial strains isolated from rice paddies in Kazakhstan. *International Journal of Hydrogen Energy* 47(37), pp. 16440–16453, DOI: 10.1016/j.ijhydene.2022.03.126.

Kovač et al. 2021 – Kovač, A., Paranos, M. and Marciuš, D. 2021. Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy* 46(16), pp. 10016–10035, DOI: 10.1016/j.ijhydene.2020.11.256.

Kopacz et al. 2019 – Kopacz, M., Kapłan, R. and Kwaśniewski, K. 2019. Evaluation of the economic efficiency of hydrogen production by lignite gasification. *Polityka Energetyczna – Energy Policy Journal* 22(4), pp. 21–36, DOI: 10.33223/epj/113369.

Kukeyeva et al. 2018 – Kukeyeva, F.T., Ormysheva, T.A., Baizakova, K.I. and Augan, M.A. 2018. Is Ili/Irtysh Rivers: A 'Casualty'of Kazakhstan–China relations. *Academy of Strategic Management Journal* 17(3), pp. 1–2. [Online] https://www.abacademies.org/articles/Is-ili-irtysh-rivers [Accessed: 2023-11-10].

Kumar, S.S and Himabindu, V. 2019. Hydrogen production by PEM water electrolysis. A review. *Materials Science for Energy Technologies* 2(3), pp. 442–454, DOI: 10.1016/j.mset.2019.03.002.

Kumar, S.S and Lim, H. 2022. An overview of water electrolysis technologies for green hydrogen production. *Energy Reports* 8, pp. 13793–13813, DOI: 10.1016/j.egyr.2022.10.127.

Kumekov, S. and Alinov, M. 2013. Nuclear Power Engineering in Kazakhstan in the Context of the New Energy and Environmental Strategy. *Problems of Economic Transition* 56(8), pp. 51–57, DOI: 10.2753/PET1061-1991560803.

Kusmambetov, K.D. and Suleimenova, S.Z. 2022. Water Resources as the Material Basis for Further Strategic Development of the Republic of Kazakhstan. *Journal of Environmental Management & Tourism* 13(1), pp. 99–106, DOI: 10.14505/jemt.v13.1(57).08.

Laldjebaev et al. 2021 – Laldjebaev, M., Isaev, R. and Saukhimov, A. 2021. Renewable energy in Central Asia: An overview of potentials, deployment, outlook, and barriers. *Energy Reports* 7, pp. 3125–3136, DOI: 10.1016/j.egyr.2021.05.014.

Lam et al. 2019 – Lam, C.Y., Fuse, M. and Shimizu, T. 2019. Assessment of risk factors and effects in hydrogen logistics incidents from a network modeling perspective. *International Journal of Hydrogen Energy* 44(36), pp. 20572–20586, DOI: 10.1016/j.ijhydene.2019.05.187.

Leonzio et al. 2022 – Leonzio, G., Fennell, P.S. and Shah, N. 2022. Analysis of technologies for carbon dioxide capture from the air. *Applied Sciences* 12(16), DOI: 10.3390/app12168321.

Liu, H. and Liu, S. 2021. Life cycle energy consumption and GHG emissions of hydrogen production from underground coal gasification in comparison with surface coal gasification. *International Journal of Hydrogen Energy* 46(14), pp. 9630–9643, DOI: 10.1016/j.ijhydene.2020.12.096.

Liu et al. 2022 – Liu, H., Guo, W. and Liu, S. 2022. Comparative techno-economic performance analysis of underground coal gasification and surface coal gasification based coal-to-hydrogen process. *Energy* 258, DOI: 10.1016/j.energy.2022.125001.

Megía et al. 2021 – Megía, P.J., Vizcaíno, A.J., Calles, J.A. and Carrero, A. 2021. Hydrogen production technologies: from fossil fuels toward renewable sources. A mini review. *Energy & Fuels* 35(20), pp. 16403–16415, DOI: 10.1021/acs.energyfuels.1c02501.

Minazhova et al. 2023 – Minazhova, S., Akhambayev, R., Shalabayev, T., Bekbayev, A., Kozhageldi, B. and Tvaronavičienė, M. 2023. A Review on Solar Energy Policy and Current Status: Top 5 Countries and Kazakhstan. *Energies* 16(11), DOI: 10.3390/en16114370.

Ministry of Energy of the Republic of Kazakhstan 2022. The Ministry of Energy and the European Bank for Reconstruction and Development (EBRD) have signed a memorandum of cooperation. [Online] https://www.gov.kz/memleket/entities/energo/press/news/details/179407?lang=ru [Accessed: 2022-10-27] (*in Russian*).

Ministry of Energy of the Republic of Kazakhstan 2023. The uranium industry. [Online] https://www.gov.kz/memleket/entities/energo/activities/4908?lang=ru [Accessed: 2023-11-23] (*in Russian*).

Ministry of Foreign Affairs of the Republic of Kazakhstan 2021. Kazakhstan joins the race for the production of «green» hydrogen. [Online] https://www.gov.kz/memleket/entities/mfa/press/news/details/269278?lang=ru; [Accessed: 2021-11-09] (*in Russian*).

Molenda, J. 2008. The fundamental meaning of scientific research for development of hydrogen economy. *Polityka Energetyczna – Energy Policy Journal* 11(2), pp. 61–68.

Mosca et al. 2020 – Mosca, L., Jimenez, J.A., Wassie, S.A., Gallucci, F., Palo, E., Colozzi, M., Taraschi, S. and Galdieri, G. 2020. Process design for green hydrogen production. *International journal of hydrogen energy* 45(12), pp. 7266–7277, DOI: 10.1016/j.ijhydene.2019.08.206

Mouraviev, N. 2021. Renewable energy in Kazakhstan: Challenges to policy and governance. *Energy Policy* 149, DOI: 10.1016/j.enpol.2020.112051.

Mukhambet et al. 2022 – Mukhambet, Y., Shah, D., Tatkeyeva, G. and Sarbassov, Y. 2022. Slow pyrolysis of flax straw biomass produced in Kazakhstan: Characterization of enhanced tar and high-quality biochar. *Fuel* 324, DOI: 10.1016/j.fuel.2022.124676.

Mukhamediev et al. 2019 – Mukhamediev, R.I., Mustakayev, R., Yakunin, K., Kiseleva, S. and Gopejenko, V. 2019. Multi-criteria spatial decision making supportsystem for renewable energy development in Kazakhstan. *IEEE Access* 7, pp. 122275–122288, DOI: 10.1109/ACCESS.2019.2937627.

Mukhtarov et al. 2020 – Mukhtarov, S., Humbatova, S., Seyfullayev, I. and Kalbiyev, Y. 2020. The effect of financial development on energy consumption in the case of Kazakhstan. *Journal of Applied Economics* 23(1), pp. 75–88, DOI: 10.1080/15140326.2019.1709690.

Noussan et al. 2020 – Noussan, M., Raimondi, P.P., Scita, R. and Hafner, M. 2020. The role of green and blue hydrogen in the energy transition – A technological and geopolitical perspective. *Sustainability* 13(1), DOI: 10.3390/su13010298.

Noyan et al. 2023 – Noyan, O.F., Hasan, M.M. and Pala, N. 2023. A Global Review of the Hydrogen Energy Eco-System. *Energies* 16(3), DOI: 10.3390/en16031484.

Nuclear power in Kazakhstan 2022. Nuclear power in Kazakhstan: pros and cons (*Atomnaya energetika v Kazakhstane: za i protiv*). [Online] https://kazpravda.kz/n/atomnaya-energetika-v-kazahstane-za-i-protiv/ [Accessed 30 May 2022] (*in Russian*).

Nurlankyzy et al. 2016 – Nurlankyzy, S., Xiong, Y., Luo, M. and Wang, K. 2016. Investigation on solar energy industry development model in Kazakhstan. *Open Journal of Business and Management* 4(3), pp. 393–400, DOI: 10.4236/ojbm.2016.43041.

Nurseiit, N.A. and Charman, K. 2018. Selection of the optimal way of development for the oil dependent economy of Kazakhstan. *Eurasian Journal of Economics and Finance* 6(1), pp. 25–34, DOI: 10.15604/ejef.2018.06.01.003.

Official information resource 2022. Amendments in the field of electric power industry, construction of generating plants, potential for the development of nuclear energy – the state of Kazakhstan's thermal power industry today. [Online] https://primeminister.kz/ru/news/reviews/popravki-v-oblasti-elektroenergetiki- [Accessed: 2022-02-14] (*in Russian*).

Opakhai, S. and Kuterbekov, K. 2023. Metal-Supported Solid Oxide Fuel Cells: A Review of Recent Developments and Problems. *Energies* 16(12), DOI: 10.3390/en16124700.

Panchenko et al. 2023 – Panchenko, V.A., Daus, Y.V., Kovalev, A.A., Yudaev, I.V. and Litti, Y.V. 2023. Prospects for the production of green hydrogen: Review of countries with high potential. *International Journal of Hydrogen Energy* 48(12), pp. 4551–4571, DOI: 10.1016/j.ijhydene.2022.10.084.

Park et al. 2021 – Park, J.B., Adibayeva, A. and Saari, D. 2021. Contestation and collaboration for water resources: comparing the emerging regional water governance of the Aral Sea, Irtysh River, and Mekong River. *Journal of Asian and African Studies* 56(6), pp. 1121–1143, DOI: 10.1177/0021909620957689.

Parkhomchik, L.A. 2020. Current hydropower potential of Kazakhstan. *Water resources management in Central Asia*, pp. 125–141, DOI: 10.1007/698_2020_620.

Pinsky et al. 2020 – Pinsky, R., Sabharwall, P., Hartvigsen, J. and O'Brien, J. 2020. Comparative review of hydrogen production technologies for nuclear hybrid energy systems. *Progress in Nuclear Energy* 123, DOI: 10.1016/j.pnucene.2020.103317.

Poberezhskaya, M. and Bychkova, A. 2022. Kazakhstan's climate change policy: reflecting national strength, green economy aspirations and international agenda. *Post-communist economies* 34(7), pp. 894–915, DOI: 10.1080/14631377.2021.1943916.

Poluzzi et al. 2022 – Poluzzi, A., Guandalini, G. and Romano, M.C. 2022. Flexible methanol and hydrogen production from biomass gasification with negative emissions. *Sustainable Energy & Fuels* 6(16), pp. 3830–3851, DOI: 10.1039/D2SE00661H.

Radelyuk et al. 2019 – Radelyuk, I., Tussupova, K., Zhapargazinova, K., Yelubay, M. and Persson, M. 2019. Pitfalls of wastewater treatment in oil refinery enterprises in Kazakhstan, a system Approach. *Sustainability* 11(6), DOI: 10.3390/su11061618.

Raihan, A. and Tuspekova, A. 2022. Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: New insights from Kazakhstan. *World Development Sustainability* 10(5), DOI: 10.1007/s40710-023-00618-x.

Renewable Electricity 2022. Renewable Electricity. [Online] https://www.iea.org/reports/renewable-electricity [Accessed: 2022-09-15].

Şahin, S. and Şahin, H.M. 2021. Generation-IV reactors and nuclear hydrogen production. *International Journal of Hydrogen Energy* 46(57), pp. 28936–28948, DOI: 10.1016/j.ijhydene.2020.12.182.

Satayeva et al. 2022 – Satayeva, A., Baimenov, A., Azat, S., Zhantikeyev, U., Seisenova, A. and Tauanov, Z. 2022. Review on coal fly ash generation and utilization for resolving mercury contamination issues in Central Asia: Kazakhstan. *Environmental Reviews* 30(3), pp. 418–437, DOI: doi.org/10.1139/er-2021-0035

Sea Highways of the Black and Caspian Seas 2009. Sea Highways of the Black and Caspian Seas. [Online] http://www.traceca-org.org/fileadmin/fm-dam/TAREP/61cpm/61cpm2_ru.pdf [Accessed: 2009-06-14].

Seidaliyeva et al. 2024 – Seidaliyeva, A., Kabdushev, S., Baipakbayeva, S., Kopishev, E. and Suleimenov, I. 2024. The diversification of energy sources in Kazakhstan as a way to dampen the consequences of a predicted crisis. *Polityka Energetyczna – Energy Policy Journal* 27(1), pp. 173–188, DOI: 10.33223/epj/171442.

Shi, X. and Variam, H.M. 2016. Gas and LNG trading hubs, hub indexation and destination flexibility in East Asia. *Energy Policy* 96, pp. 587–596, DOI: 10.1016/j.enpol.2016.06.032.

Sinha et al. 2022 – Sinha, A.S., Ojha, U., Alam, Z. and Tripathi, AA. 2022. Production of Hydrogen via Water Splitting Using Photocatalytic and Photoelectrocatalytic Route. [In:] *Clean Energy Technologies-Hydrogen and Gasification Processes. IntechOpen*. DOI: 10.5772/intechopen.106915.

Smagulova et al. 2023 – Smagulova, S., Yermukhanbetova, A., Nurgaliyeva, K., Sariya, B., Baimukasheva, Z., Manap, A., Koyshinova, G. and Akimbekova, C. 2023. The Impact of Energy Production on the Introduction of ICT and the Growth of AIC in Kazakhstan. *International Journal of Energy Economics and Policy* 13(1), DOI: 10.32479/ijeep.13765.

Soja et al. 2023 – Soja, R.J., Gusau, M.B., Ismaila, U. and Garba, N.N. 2023. Comparative analysis of associated cost of nuclear hydrogen production using IAEA hydrogen cost estimation program. *International Journal of Hydrogen Energy*, DOI: 10.1016/j.ijhydene.2023.03.133.

Solovyev et al. 2019 – Solovyev, A.A., Maznoy, A.S., Kuterbekov, K.A., Nurkenov, S.A., Opakhai, S., Kirdyashkin, A.I., Kitler, V.D., Pichugin, N.S., Rabotkin, S.V. and Ionov, I.V. 2019. Porous Ni–Al–CGO Cermet for Use in Solid Oxide Fuel Cells. *International Journal of Self-Propagating High-Temperature Synthesis* 28, pp. 256–261, DOI: 10.3103/S1061386219040137.

Song et al. 2022 – Song, H., Yang, G., Xue, P., Li, Y., Zou, J., Wang, S., Yang, H. and Chen, H. 2022. Recent development of biomass gasification for H2 rich gas production. *Applications in Energy and Combustion Science* 10; DOI: 10.1016/j.jaecs.2022.100059.

Sputnik Kazakhstan 2022. Kazakhstan has decided on the construction site of the nuclear power plant: what is known about the village of Ulken. [Online] https://ru.sputnik.kz/20220614/kazakhstan-opredelilsya-s-mestom-stroitelstva-aes-chto-izvestno-o-poselke-ulken-25494861.html [Accessed: 2022-05-30].

Starowicz et al. 2023 – Starowicz, A., Rusanowska, P. and Zieliński, M. 2023. Photovoltaic cell–the history of invention–review. *Polityka Energetyczna-Energy Policy Journal* 26(1), pp. 169–180, DOI: 10.33223/epj/161290.

Tańczyk et al. 2009 – Tańczyk, M., Warmuziński, K. and Jaschik, M. 2009. Hydrogen separation from gaseous product of the process of high temperature conversion of coke-oven gas. *Polityka Energetyczna – Energy Policy Journal* 12(2), pp. 577–591.

Tarhan, C. and Çil, M.A. 2021. A study on hydrogen, the clean energy of the future: Hydrogen storage methods. *Journal of Energy Storage* 40< DOI: 10.1016/j.est.2021.102676.

Tazhibayeva et al. 2009 – Tazhibayeva, I., Kenzhin, E., Shestakov, V., Chikhray, Y., Kulsartov, T., Azizov, E., Filatov, O. and Chernov, V. 2009. Material science activities for fusion reactors in Kazakhstan. *Journal of nuclear materials* 386, pp. 15–18, DOI: 10.1016/j.jnucmat.2008.12.050.

Temirgaliyeva, N. and Junussova, M. 2020. Renewable Electricity Production and Sustainability of the National and Regional Power Systems of Kazakhstan. *Silk Road: A Journal of Eurasian Development* 2(1), pp. 35–53, DOI: 10.16997/srjed.15.

Tengri News 2013. Wind energy potential in Kazakhstan is 10 times greater than the need for electricity. [Online] https://tengrinews.kz/kazakhstan_news/potentsial-vetroenergetiki-kazahstane-10-prevyishaet-228854/ [Accessed: 2013-02-20].

Terehovics et al. 2017 – Terehovics, E., Khabdullin, A., Khabdullin, A., Khabdullina, Z., Khabdullina, G., Veidenbergs, I. and Blumberga, D. 2017. Why solar electricity has high potential for Kazakhstan industries. *Energy Procedia* 113, pp. 417–422, DOI: 10.1016/j.egypro.2017.04.026.

Thaysen et al. 2021 – Thaysen, E.M., McMahon, S., Strobel, G.J., Butler, I.B., Ngwenya, B.T., Heinemann, N., Wilkinson, M., Hassanpouryouzband, A., McDermott, C.I. and Edlmann, K. 2021. Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. *Renewable and Sustainable Energy Reviews* 151, DOI: 10.1016/j.rser.2021.111481.

The oil and gas sector 2020. The oil and gas sector. [Online] http://www.kmgep.kz/rus/about_kazakhstan/oil_and_gas_sector/ [Accessed: 2023-10-18].

The potential of wind energy in Kazakhstan 2020. The potential of wind energy in Kazakhstan. [Online] https://www.eurasian-research.org/publication/potential-of-wind-energy-in-kazakhstan/?lang=ru; [Accessed: 2020-11-24].

Tleubergenova et al. 2023 – Tleubergenova, A., Abuov, Y., Danenova, S., Khoyashov, N., Togay, A. and Lee, W. 2023. Resource assessment for green hydrogen production in Kazakhstan. *International Journal of Hydrogen Energy* 48(43), pp. 16232–16245, DOI: 10.1016/j.ijhydene.2023.01.113.

Tleuken et al. 2022 – Tleuken, A., Tokazhanov, G., Jemal, K.M., Shaimakhanov, R., Sovetbek, M. and Karaca, F. 2022. Legislative, Institutional, Industrial and Governmental Involvement in Circular Economy in Central Asia: A Systematic Review. *Sustainability* 14(13), DOI: 10.3390/su14138064.

Tleuken et al. 2022 – Tleuken, A., Tokazhanov, G., Jemal, K.M., Shaimakhanov, R., Sovetbek, M. and Karaca, F. 2022. Legislative, Institutional, Industrial and Governmental Involvement in Circular Economy in Central Asia: A Systematic Review. *Sustainability* 14(13), DOI: 10.3390/su14138064.

Tokmurzin et al. 2022 – Tokmurzin, D., Ra, H.W., Yoon, S.M., Yoon, S.J., Lee, J.G., Seo, M.W. and Adair, D. 2022. Pyrolysis characteristics of Kazakhstan coals in non-isothermal and isothermal conditions. *International Journal of Coal Preparation and Utilization* 42(3), pp. 254–274, DOI: 10.1080/19392699.2019.1594793.

Tomczyk, P. 2009. Prospects and obstacles of hydrogen economy development. *Polityka Energetyczna – Energy Policy Journal* 12(2), pp. 593–607.

Turgali et al. 2021 – Turgali, D., Kopeyeva, A., Dikhanbayeva, D. and Rojas-Solórzano, L. 2021. Potential impact of global warming on wind power production in Central Asia. *Environmental Progress & Sustainable Energy* 40(4), DOI: 10.1002/ep.13626.

Turganbayeva, T. 2020. The Impact of Oil and Natural Gas to the Foreign Policy of Kazakhstan. *ESAM Ekonomik ve Sosyal Araştırmalar Dergisi* 1(2), pp. 225–244. [Online] https://dergipark.org.tr/en/download/article-file/1276257 [Accessed: 2024-01-23].

Turoń, K. 2020. Hydrogen-powered vehicles in urban transport systems–current state and development. *Transportation Research Procedia* 45, pp. 835–841, DOI: 10.1016/j.trpro.2020.02.086.

Umarova et al. 2022 – Umarova, G., Batyrova, G., Tlegenova, Z., Kononets, V., Balmagambetova, S., Umarov, Y., Yessengaliyeva, I. and Mamyrbayev, A. 2022. Essential Trace Elements in Scalp Hair of Residents across the Caspian Oil and Gas Region of Kazakhstan. *Toxics* 10(7), DOI: 10.3390/toxics10070364.

UNECE 2023. Sustainable Hydrogen Production Pathways in Eastern Europe, the Caucasus and Central Asia. [Online] https://unece.org/sites/default/files/2023-03/EN_Sustainable%20Hydrogen%20Production%20Pathways_final_0.pdf [Accessed: 2023-06-05].

University of Central Asia 2022. Renewable energy sources in Central Asia: potential, use, prospects and barriers. [Online] https://ucentralasia.org/media/ucflputa/uca-ippa-wp71vozobnovlyaemie-istochnikirus.pdf [Accessed: 2022-10-13].

Uranium and Nuclear Power in Kazakhstan 2023. Uranium and Nuclear Power in Kazakhstan. [Online] https://world-nuclear.org/information-library/country-profiles/countries-g n/kazakhstan.aspx; [Accessed: 2023-05-10].

Uteubayev, T. 2016. Comparative analysis of human development in Kazakhstan and other Eurasian economic union countries. *International Journal of Economics and Financial Issues* 6(4), pp. 1419–1423. [Online] https://dergipark.org.tr/en/download/article-file/366189 [Accessed: 2023-11-14].

Vechkinzova et al. 2021 – Vechkinzova, E., Petrenko, Y., Matkovskaya, Y.S. and Koshebayeva, G. 2021. The dilemma of long-term development of the electric power industry in Kazakhstan. *Energies* 14(9), DOI: 10.3390/en14092374.

Więcław-Solny, L. and Łabojko, G. 2010. Application of membrane reactor for synthesis gas production–research results. *Polityka Energetyczna – Energy Policy Journal* 13(2), pp. 459–471.

Więcław-Solny et al. 2009 – Więcław-Solny, L., Łabojko, G. and Babiński, P. 2009. Possibilities of carbon dioxide industrial utilization-research on CO2 application in synthesis gas production. *Polityka Energetyczna – Energy Policy Journal* 12(2), pp. 633–643.

World Resources Institute 2015. Ranking the World's Most Water-Stressed Countries in 2040. [Online] https://www.wri.org/insights/ranking-worlds-most-water-stressed-countries-2040?trk=public_post_comment-text; [Accessed: 2015-08-26].

Yakubson, K.I. 2020. Prospects for Production and Use of Hydrogen as one of Directions of the Development of Low-Carbon Economy in the Russian Federation. *Russian Journal of Applied Chemistry* 93, pp. 1775–1795, DOI: 10.1134/S1070427220120010.

Yu et al. 2021 – Yu, M., Wang, K. and Vredenburg, H. 2021. Insights into low-carbon hydrogen production methods: Green, blue and aqua hydrogen. *International Journal of Hydrogen Energy* 46(41), pp. 21261–21273, DOI: 10.1016/j.ijhydene.2021.04.016.

Zhang et al. 2021 – Zhang, S.C., Yang, X.Y., Xu, W. and Fu, Y.J. 2021. Contribution of nearly-zero energy buildings standards enforcement to achieve carbon neutral in urban area by 2060. *Advances in Climate Change Research* 12(5), pp. 734–743, DOI: 10.1016/j.accre.2021.07.004.

Zhang et al. 2021 – Zhang, X., Jiao, K., Zhang, J. and Guo, Z. 2021. A review on low carbon emissions projects of steel industry in the World. *Journal of Cleaner Production* 306, DOI: 10.1016/j.jclepro.2021.127259.

Zhang et al. 2022 – Zhang, J., Ling, B., He, Y., Zhu, Y. and Wang, Z. 2022. Life cycle assessment of three types of hydrogen production methods using solar energy. *International Journal of Hydrogen Energy* 47(30), pp. 14158–14168, DOI: 10.1016/j.ijhydene.2022.02.150.

Zholdayakova et al. 2022 – Zholdayakova, S., Abuov, Y. and Zhakupov, D. 2022. Toward a Hydrogen Economy in Kazakhstan. *ADBI Working Paper Series* 1344, DOI: 10.56506/IWLU3832.

Zhunussova et al. 2020 – Zhunussova, G.Z., Ratner, S.V., Zhunussova, G.Z., Nurmukhanova, G.Z. and Shaihutdinova, A.K. 2020. Renewable energy in Kazakhstan: challenges and prospects. *International Energy Journal* 20(3), pp. 311–324. [Online] https://www.thaiscience.info/Journals/Article/IENJ/10992376.pdf [Accessed: 2023-11-12].

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Energetyka wodorowa w Kazachstanie: perspektywy rozwoju

Streszczenie

Kazachstan posiada znaczne zasoby naturalne, w tym węgiel, ropę naftową, gaz ziemny i uran, a także ma znaczny potencjał w zakresie wykorzystania odnawialnych źródeł energii, takich jak wiatr, energia słoneczna, energia wodna i biomasa. Jednak obecnie kraj w dużym stopniu opiera się na paliwach kopalnych do wytwarzania energii elektrycznej. Elektrownie węglowe wytwarzają 75% całkowitej produkcji energii elektrycznej, co budzi obawy dotyczące emisji gazów cieplarnianych i ich szkodliwego wpływu na zdrowie ludzkie i środowisko. W grudniu 2020 r. podczas Szczytu Ambicji Klimatycznych Prezydent Kazachstanu ogłosił nowy cel dla kraju, jakim jest osiągnięcie neutralności emisyjnej do 2060 r. Aby osiągnąć ten cel, przed rządem stoi ambitne zadanie opracowania strategii rozwoju energetyki wodorowej w Kazachstanie.

W niniejszym przeglądzie szeroko omówiono główne zasoby energetyczne Kazachstanu, potencjał niskoemisyjnej i zielonej produkcji wodoru, istniejące i przyszłe projekty pilotażowe w obszarze wodoru, a także wyzwania i bariery utrudniające rozwój energetyki wodorowej w Kazachstanie. Autorzy uwzględniają istniejące badania, raporty krajowe, strategie energetyczne i plany, aby omówić perspektywy rozwoju energetyki wodorowej w Kazachstanie. Przejście na energię wodorową w Kazachstanie wymaga opracowania kompleksowego planu działania, który uwzględnia różne aspekty, takie jak produkcja, rozwój infrastruktury, wsparcie polityczne i współpraca międzynarodowa. Obecnie w kraju brakuje planu działania dotyczącego rozwoju energii wodorowej, który uwzględniałby te kluczowe aspekty. Dlatego w wyniku tego przeglądu opracowano nowy plan działania dotyczący produkcji wodoru do 2040 roku w Kazachstanie, uwzględniający różne technologie. Autorzy uważają, że niniejszy plan działania będzie cenną informacją dla rządu przy opracowywaniu krajowej strategii aktywnego rozwoju energetyki wodorowej w Kazachstanie.

SŁOWA KLUCZOWE: energia wodorowa, Kazachstan, odnawialne źródła energii, zielony wodór, neutralność emisyjna