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The role of hydrogen in ensuring Kazakhstan's energy security

Abstract: The article aims to analyse Kazakhstan's energy system, identify key parameters of energy security, and explore new opportunities, including the role of hydrogen energy, in ensuring the sustainability of the country's energy system. The study utilised methods of scientific knowledge such as analysis, synthesis, modelling, and SWOT analysis. It assessed the dynamics of electricity generation and oil production in Kazakhstan, using statistical methods of modelling and forecasting. The study identified the current state and possible future trends, highlighting the impact of high dependence on oil exports on Kazakhstan's economy and vulnerability to price fluctuations in world markets. A comparative analysis of the energy systems of other countries and regions was conducted to identify problems and potential solutions. The environmental and

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climate impacts of various energy sources, including coal, oil, gas, and renewable sources, were analysed. The study examined market mechanisms to support renewable energy, such as renewable electricity certification, and their impact on sector revenues. A conceptual approach to energy security was considered, analysing economic factors like fuel prices and capital costs of transitioning to renewable energy. Various scenarios for developing Kazakhstan's energy system were assessed, including projections of renewable energy use and changes in fuel consumption. The results of this study can inform the development of Kazakhstan's energy policy. Understanding the current state and trends in the energy sector allows for identifying key problems and potential development opportunities.

Keywords: SWOT analysis, renewable energy, carbon neutrality, strategy development, fossil sources

Introduction

It is important to undertake this study because Kazakhstan is at a critical juncture in its energy development when the country is actively pursuing carbon neutrality and facing significant energy and environmental challenges. Understanding the key parameters of energy security and the opportunities for the introduction of new technologies such as hydrogen energy is critical for the development of strategies aimed at achieving sustainability and environmental efficiency in the country's energy sector, which makes the study urgent and important at this very moment. The problematics of this study include the need to identify the key parameters of energy security in the context of Kazakhstan's pursuit of carbon neutrality, as well as to explore new opportunities, including the role of hydrogen energy, and their potential in ensuring the stability and sustainability of the country's energy system. In other words, the issues include finding ways to balance environmental and economic interests in Kazakhstan's energy sector, as well as assessing the role of innovative technologies in achieving energy security and sustainability.

Kazakhstan is a country with vast energy resources, and is currently at a pivotal moment in its energy transition, aligning with global sustainability goals and carbon neutrality commitments. The country aims to reduce its dependency on fossil fuels, particularly coal, and increase the share of renewable energy sources, such as wind, solar, and green hydrogen, by 2060. However, the heavy reliance on coal-fired power generation poses significant environmental challenges. The energy sector remains vital for the economy, particularly through oil and gas exports, but volatility in global energy prices presents economic vulnerabilities.

Located in the heart of Central Asia, the Republic of Kazakhstan is rich in fossil resources, including uranium, coal, oil, and gas. Since independence, Kazakhstan has demonstrated significant progress in developing its oil and gas sector and has earned an important role in the global energy market. However, fossil fuels remain the main source of energy, which poses significant risks to the country's sustainable development. The Strategy for Achieving Carbon Neutrality (SACN) of the Republic of Kazakhstan until 2060 came into force in 2023 (Decree of the Presi-

dent… 2023). According to the SACN, the country will almost completely abandon the burning of fossil fuels by 2060, except for carbon dioxide emissions, which will be offset by absorption by forest plantations or carbon capture and storage technologies. Thus, Kazakhstan's energy sector must completely change over the next 40 years, eliminating coal and gas-fired generation of heat and electricity, and closing power plants.

In conformity with Ibrayeva (2023), due to its low atomic mass, hydrogen requires a special technical and legislative framework for its production, storage, transport, and utilisation, which is currently lacking in Kazakhstan. However, the existing infrastructure of the oil and gas sector and the significant potential for the development of renewable energy sources could be the basis for starting operations. With the growing global demand for green hydrogen, Kazakhstan has the potential for large-scale production for export and needs a clean product to reduce carbon dioxide emissions in the energy sector and narrow industries. The author of the study has not considered the potential economic and social impacts of developing a green hydrogen industry in Kazakhstan. This includes questions about job creation, the impact on the country's economic structure, and ensuring that the benefits of this development are accessible and equitably distributed among different segments of the population.

In their study, Aubakirova et al. (2023) showed that the transformation of the energy system has a significant impact on the economy of the country. It was found that the key method to strengthen Kazakhstan's position in international value chains is the introduction of a strategy of decarbonisation of industry that considers national interests. Given the continuing high levels of energy intensity globally, the progress of extractive industries requires active government assistance and strengthened public-private partnerships. This study did not consider the influence of political and international factors on the implementation of the industrial decarbonisation strategy in Kazakhstan.

In their article, Esenzhol et al. (2023) considered the possibility of utilising agricultural waste for bioenergy production. The main objective of the project was to develop a pilot energy complex designed to produce thermal energy from biomass or animal waste. This complex includes a biofuel production site, a biogas synthesis plant, and a thermal generator, which is a new type of hot water boiler for thermal energy production. The authors of the article did not consider the potential environmental impacts of the process of bioenergy production from agricultural waste, as well as the possible socio-economic consequences of introducing such technologies into agricultural communities.

According to Shakulikova and Akhmetov (2021), given the continuous global warming and increasing greenhouse gas emissions, decarbonisation requires an accelerated increase in energy efficiency and sustainable energy use. The application of behavioural analysis also plays an important role in this complex process in developing countries, including Kazakhstan, where a significant increase in energy demand is expected in the future and where there is a huge potential for energy efficiency improvements.

A study assessing the role of hydrogen in addressing energy security and environmental sustainability in Kazakhstan is significant. The development of green hydrogen represents a key opportunity for the country to reduce its carbon footprint, enhance its energy system's resilien-

ce, and offer new export opportunities in a global market increasingly focused on green energy (Ivanenko 2023; Metaksa et al. 2018). By analysing Kazakhstan's energy security parameters, conducting a SWOT analysis of hydrogen energy, and modelling potential future scenarios, this study provides a comprehensive framework for understanding the risks and opportunities associated with the country's energy transition. It highlights how hydrogen can contribute to energy diversification, reduce dependency on fossil fuels, and ensure long-term sustainability for Kazakhstan's energy sector. The findings can inform policymakers and stakeholders about strategic decisions for developing the country's energy infrastructure and integrating hydrogen into its energy mix.

While this study offers valuable insights into Kazakhstan's energy security and the potential role of hydrogen energy, it is not without limitations. A notable limitation is the absence of comprehensive, long-term data on hydrogen energy infrastructure and its economic impact in Kazakhstan. This limitation affects the accuracy of projections related to hydrogen energy development and its feasibility for large-scale implementation. Furthermore, the study primarily concentrates on technical and environmental aspects, with less attention devoted to socio-economic factors, such as the potential impact on employment and local communities. It would be beneficial for future research to address these areas to gain a more comprehensive understanding of the transition to hydrogen energy in Kazakhstan.

The purpose of this article is to analyse Kazakhstan's energy system, identify the main parameters of energy security, and explore new perspectives, including the potential role of hydrogen energy, in ensuring the sustainability of the country's energy system. This study seeks to find solutions to the three tasks set:

1. Identification of key parameters of Kazakhstan's energy security.
2. Conduct a SWOT analysis of energy security, including in the context of hydrogen energy development.
3. Model the possible scenarios for the future development of Kazakhstan's energy system.

1. Materials and methods

Given that Kazakhstan is rich in cheap and accessible energy resources, the achievement of this parameter is considered in terms of compliance with several economic, technological, infrastructural, social, and political conditions. Thus, the following parameters (and conditions for their observance) of Kazakhstan's energy security have been selected, which together determine the population's permanent access to energy sources at an affordable price: energy access to end consumers; energy access within the country; energy efficiency improvement; energy grid modernisation; grid balancing; energy independence.

The study was based on the analysis of data on electricity production and consumption in Kazakhstan from various sources, as well as on the production and export of energy resources

such as oil and gas. Statistical modelling and forecasting techniques were used to analyse the dynamics of electricity generation and oil production, which allowed assessing the current state and predicting possible future trends. The study included an analysis of the economic aspects of Kazakhstan's energy sector, such as the impact of high dependence on oil exports on the country's economy and vulnerability to price fluctuations in world markets. The work included a comparative analysis of the energy systems of other countries and regions to identify the peculiarities and problems of Kazakhstan's energy sector and to identify possible solutions. The study also examined the environmental aspects of various energy sources, including coal, oil, gas, and renewables, and their impact on the environment and climate. The implementation of market mechanisms to support renewable energy was investigated, including the possibilities of renewable electricity certification and their impact on revenues in the sector. The initial stage of the study was to analyse the conceptual approach to energy security based on the International Energy Agency definition. In the course of the study, an economic analysis was carried out, which included an assessment of the availability of energy resources at an affordable price.

In addition, a comparative analysis of energy consumption by different sectors of the economy, such as industry and population, was carried out. The state of the infrastructure and technical systems of the energy sector, including the state of the electricity supply networks, was also analysed. As part of the economic analysis, economic factors affecting Kazakhstan's energy security, such as fuel prices and capital costs of transition to renewable energy sources, were assessed. A comparative analysis of different aspects of energy security, such as fuel access and renewable energy prospects, was also carried out to identify specificities and highlight challenges and prospects. The analyses used evaluated various scenarios for the development of Kazakhstan's energy system, including projections of renewable energy use and changes in fuel consumption.

A SWOT analysis was used to identify the strengths, weaknesses, opportunities, and threats to Kazakhstan's energy security. It is important to note that opportunities that strengthen Kazakhstan's energy security include the development of renewable energy and hydrogen energy. In this regard, to better reflect the role of hydrogen in Kazakhstan's future, the paper proposes a separate SWOT analysis dedicated to hydrogen energy in Kazakhstan. This SWOT analysis demonstrated the most promising areas of hydrogen in the country and determined the boundaries of the potential and risks of development of this area. The article proposes 5 following modelling scenarios selected based on SWOT analysis and existing strategic directions of Kazakhstan's development: moving away from coal; developing of renewable energy sources (RES); hydrogen for balancing; green hydrogen for export; and global decline in oil and gas prices.

2. Results

2.1. Kazakhstan's energy sector

Despite Kazakhstan's efforts to develop renewable energy sources, the country's energy sector remains based on coal-fired generation (Fig. 1). It is important to note that almost 100% of Kazakhstan's heat energy is produced through coal combustion. At the same time, as of 2020, there were 68 thermal power plants in Kazakhstan, of which 28 were coal-fired, 38 were gas-fired and 2 were oil-fired. 27 of these plants do not generate electricity – only heat. The average age of coal-fired power plants is 55 years, and 64% of all power plants in Kazakhstan are older than 30 years (Decree of the President… 2023).

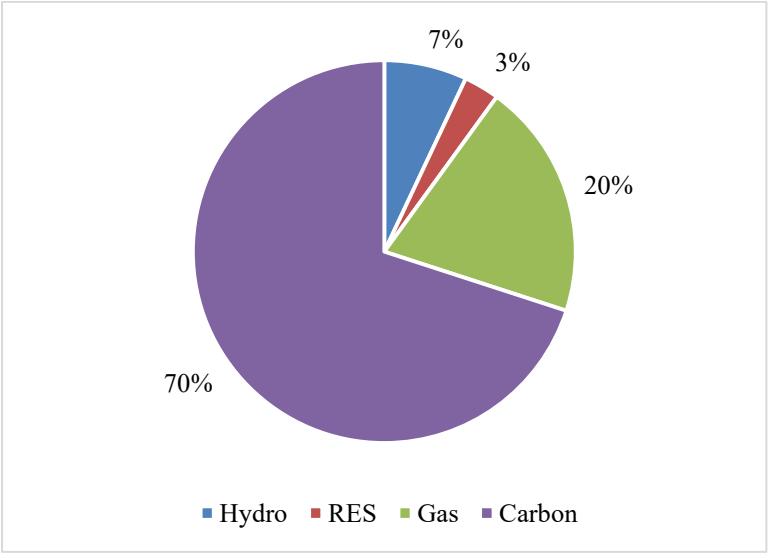

Fig. 1. Electricity generation in Kazakhstan by source
Source: compiled by the authors based on Electricity production in the Republic of Kazakhstan (2022)

Rys. 1. Generacja energii elektrycznej w Kazachstanie według źródła

An important feature of the country's energy sector is that, for many years, Kazakhstan has remained a net exporter of primary energy resources, which include oil, gas, coal, and primary electricity (not including uranium). At the same time, global demand for these resources is expected to fall steadily due to countries' efforts to achieve carbon neutrality. Kazakhstan has significant reserves of oil and natural gas. The oil industry in the country is developing intensively and Kazakhstan is an important world exporter of crude oil. Kazakhstan's oil and gas complex

plays a key role in the development of the country and the formation of the gross domestic product (GDP). Therefore, the high dependence on oil exports makes the country vulnerable to price fluctuations in world markets. Kazakhstan ranks 17th in the world in terms of oil production, 12th in terms of proven oil reserves (3.9 billion tonnes), and 14th in terms of gas reserves – 2.7 trillion m^3 (Suraganov 2022). In 2022, oil production was 84.2 million tonnes (64.3 million tonnes exported), a decrease of 1.5 million tonnes compared to 2021. Similarly, exports decreased by 3.3% year-on-year. Kazakhstan has three major refineries and most of its oil production comes from three major fields: Tengiz, Karachaganak, and Kashagan. In 2022, the Tengiz field became the leader in oil production, producing 29.2 million tonnes.

Since independence, Kazakhstan has built a diversified oil transportation system for export and domestic market supply and has more than tripled oil production. Exports are carried out through several routes: through the Caspian Pipeline Consortium, Atyrau-Samara oil pipelines to European countries, to terminals on the Black and Baltic Seas, through the Kazakhstan-China oil pipeline to the Chinese market, and the Aktau Seaport (Ministry of Energy of… 2022). It is important to note that the major oil and gas companies present in Kazakhstan are gradually reducing capital expenditure on hydrocarbon projects, and are channelling financial resources into the development of renewable energy sources. This activity is primarily aimed at reducing greenhouse gas emissions. The coal sector is also important for Kazakhstan's energy security. It is used to generate electricity and provide heat. However, coal can be a source of pollution and greenhouse gas emissions, which creates obvious obstacles to sustainability and environmental security.

The new Environmental Code of the Republic of Kazakhstan, adopted on 1 July 2021, significantly strengthens environmental requirements for both large coal consumers (thermal power plants) and producers (Law of the Republic of Kazakhstan… 2021). By 2035, the largest stationary sources of pollution in the country will have to undergo a costly process of transition to the principles of best available techniques by European practice. At the same time, the evolution of the national emissions trading system is aimed at a significant increase in the price of carbon (from 1 USD per tonne of CO_2 in 2023), which will lead to additional costs in the coal business and, accordingly, an increase in the price of electricity and heat for end consumers. The coal industry provides 70% of electricity and satisfies fuel needs. The industry employs about 30 thousand people and has coal reserves of 33.9 billion tonnes or 2.4% of the world's total. Over the years of independence, more than 2.7 billion tonnes of coal have been extracted and about 0.8 billion tonnes have been exported. About 30 companies in the country produce coal for the population and municipal needs. In 2021, 111.7 million tonnes of coal were produced and exports amounted to 30.5 million tonnes (The future of Kazakhstan's… 2022). The future fate of the country's coal industry faces a dilemma: what to do with the country's significant coal reserves if it is necessary to completely green the industry? On the one hand, the country must give up all fossil fuels. On the other hand, due to the growth of the economy, population, and number of residential buildings and industrial facilities, there is a need to increase the generation of cheap coal-fired electricity. Kazakhstan has been the world's largest producer of natural uranium since 2009. In 2022, uranium production totalled 21.3 thousand tonnes, and in 2023 it is planned to

diversify the transport routes for uranium products. In December 2022, the first batch of fuel assemblies was delivered to China for nuclear power plants (NPP) (Development of Nuclear Energy 2023).

It is important to note that Kazakhstan is considering building an NPP with uranium and uranium product reserves and a scientific base. In 2022, a list of proven reactor technology suppliers was compiled, including China, Russia, Korea, and France. At the same time, Zhambyl district of Almaty region is the optimal area for an NPP location (Development of Nuclear Energy 2023). The volume of RES generation in 2022 was 5.11 billion kWh or 4.53% of total electricity generation. Targets for increasing the share of renewable energy sources in the country's energy mix: up to 15% in 2030 and up to 50% in 2050. It is important to note that an increase in the share of RES in the country's energy balance will ensure independence from fossil energy resources. The system of state support for RES in Kazakhstan has been in place since 2009, with the adoption of the Law of the Republic of Kazakhstan No. 165-IV "On supporting the use of renewable energy sources" (2009). Since then, support instruments for RES development have been modified and improved, ensuring a rapid and stable pace of clean energy development in Kazakhstan. Measures to support renewable electricity generation include guaranteed purchase of electricity through the RES Support Settlement and Financial Centre and exemption from payment for services of energy transmission companies. In addition, Kazakhstan has auctions for the purchase of renewable energy capacity.

More recently, market-based mechanisms to support renewable energy have also started to operate in Kazakhstan. In January 2022, Kazakhstan accredited an issuing organisation, the International REC Standard Foundation, allowing Kazakhstan's RES facilities to certify renewable electricity to increase revenues (Kazakhstan is approved… 2022). It is important to note that the high potential for renewable energy generation in Kazakhstan opens up opportunities for the production of significant quantities of green hydrogen. To illustrate the energy security parameters of the Republic of Kazakhstan, it is important to consider energy consumption trends. Figure 2 shows that despite a significant decrease in the share of energy consumption, the industrial sector remains the main consumer (28.2%). At the same time, the consumption shares of the residential, transport, and commercial sectors have increased significantly over the last 7 years. Given that industry is the main energy consumer, it is suggested to consider consumption by subsectors (Fig. 3).

Ferrous and non-ferrous metallurgy occupies more than half of the final consumption of the industrial sector – 56.5%. This is due to the subsector's need for high-temperature technologies and, consequently, high demand for thermal energy.

2.2. Key parameters of energy security

As defined by the International Energy Agency, energy security means ensuring continued access to energy sources at an affordable price. This concept has different aspects: long-term

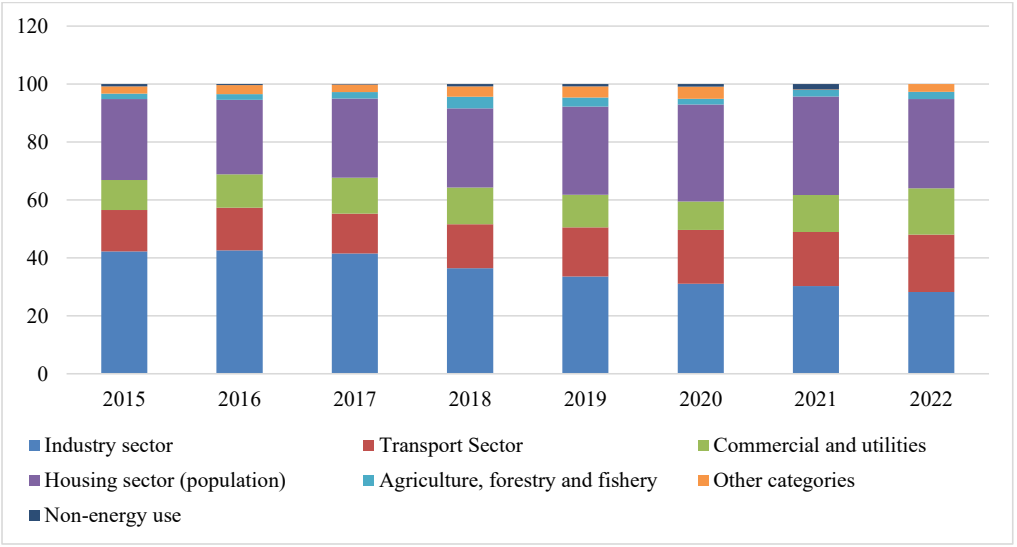

Fig. 2. Final energy consumption by economic sector [%]
Source: compiled by the authors based on Electricity production in the Republic of Kazakhstan (2022)

Rys. 2. Końcowe zużycie energii według sektora gospodarczego [%]

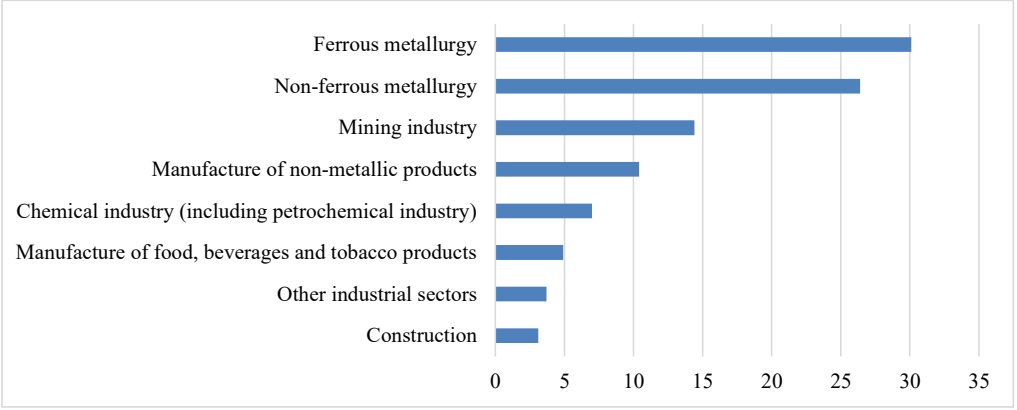

Fig. 3. Final industrial energy consumption by sub-sector in 2022 [%]
Source: compiled by the authors based on Fuel and energy balance of the Republic of Kazakhstan (2022) (2023).

Rys. 3. Końcowe zużycie energii przemysłowej według podsektora w 2022 roku [%]

energy security relates to the need to invest in energy infrastructure promptly, taking into account economic development and environmental needs. On the other hand, short-term energy security concerns the ability of energy systems to respond quickly to sudden changes in energy supply and demand (Emergency response and… 2023). Thus, the availability of affordable energy re-

sources is defined as the main parameter to be considered in terms of economic, environmental, and social aspects of sustainable development under different scenarios. At the same time, it is important to create a distinction between the two main types of electricity consumers: households and industry. This is due to differences in consumption patterns: fuel, schedule, quantity, and type of energy. For example, while the peak load hours of residential consumers are usually in the evening, industrial enterprises can operate 24 hours a day with a steady average hourly consumption. Moreover, with the shift to renewable energy, people in remote areas can get electricity where it has never been available. However, various industries, such as metallurgy, use high temperatures in their processes that are extremely difficult to achieve without the use of fossil fuels, which creates significant risks for industry and the economy of Kazakhstan as a whole (Marchenko et al. 2009; Bykov et al. 2023).

As a fossil fuel exporting country, Kazakhstan benefits from higher global energy prices. Therefore, an important factor of energy security is to ensure access to energy resources within the country, including maintaining acceptable prices and availability of technical capacity for transport, extraction, and processing of fuel. One clear example is the collapse of the heat supply in Ekibastuz in November-December 2022. At temperatures of about –30°C, some residential buildings in the city were without access to heating for more than ten days due to a series of accidents at the local combined heat and power plant (The collapse in Ekibastuz… 2022). Much of not only the heat but also the electricity infrastructure was built back in the 1970s. As of 2022, the depreciation of power grids in Kazakhstan was 65.4%, and their modernisation is difficult due to tariffs and the vast territory of the country. During the autumn-winter period of 2020–2021, 3.2 thousand technological failures occurred. It is also important to note that the central and western regions of the country are not sufficiently interconnected. Thus, the modernisation of power grids with energy efficiency improvement is the cornerstone of ensuring the energy security of the country. In this regard, the issue of attracting investment and introducing financial mechanisms to support the renewal of energy infrastructure, which usually increases tariffs for end consumers, becomes more relevant (Ishekenova 2021; Knapik 2019).

The increasing share of RES in Kazakhstan's energy mix is gradually creating a grid balancing problem. Solar and wind energy depend on weather conditions, creating uncertainty in forecasts of power generation for the next day (Serikuly et al. 2020). In case a cloudy and windless day comes unexpectedly, Kazakhstan's grid operator (Joint Stock Company Kazakhstan Electricity Grid Management Company) must promptly utilize reserve capacity, such as fossil fuel power plant batteries, which increase the amount of power output on demand. In addition, green hydrogen is a green method of energy storage and therefore one of the environmental solutions to the balancing problem. One of the most important parameters of energy security of each country is the import of energy or energy resources from other countries. Kazakhstan imports electricity from Russia in times of shortage (Table 1). It is important to note that Kazakhstan's pre-independence power system was designed to work closely with the Soviet republics and, today, "interacts in parallel" with Russia's, which is an important factor in the reliable and efficient operation of both systems (Askarov 2022; Tonkonog 2023).

Table 1. Conditions for ensuring energy security of Kazakhstan

Tabela 1. Warunki zapewnienia bezpieczeństwa energetycznego Kazachstanu

No.	Parameter	A prerequisite for ensuring energy security
1	Availability of energy resources at an affordable price	
2	Energy access to end consumers	Meeting the energy needs of business and community members fairly.
3	Domestic energy access	Maintaining adequate and affordable prices for energy resources. Maintaining the technical condition of the infrastructure for production, transport, processing, and utilisation of energy resources.
4	Improving energy efficiency	Increasing energy efficiency with continuous renewal of energy infrastructure. Development of financial support mechanisms for energy efficiency projects.
5	Modernisation of power grids	Phased modernisation of energy grids with increased energy efficiency and interconnection between regions. Attracting financial resources.
6	Balancing of electricity in the network	Introduction of electricity balancing solutions, including green hydrogen.
7	Energy independence	Reduce the need for electricity imports by increasing the stability and capacity of domestic generation.

Source: compiled by the authors.

Table 1 reflects the basic conditions for energy security in terms of certain parameters, where the availability of energy resources at an affordable price is the main parameter that requires the fulfilment of other conditions.

2.3. SWOT analysis of Kazakhstan's energy security

The SWOT analysis of Kazakhstan's energy security highlights several important aspects that need to be taken into account when developing a strategy to ensure the stability and sustainability of the country's energy system (Table 2).

It is proposed to discuss the main elements of the SWOT analysis that have the greatest impact on Kazakhstan's energy security. The main strength of Kazakhstan's energy security is its continued access to fossil fuels, thanks to the country's abundant resources. The country's well-developed oil and gas and coal industries provide acceptable prices within the market and indicate the country's intentions to further develop this area. On the other hand, access to cheap fossil fuels causes two major weaknesses in Kazakhstan's energy security: dependence on cheap fuels and difficulties in switching to renewable energy sources. The higher the price of conventional energy in the country, the faster households and businesses start to exploit renewable energy technologies. In the case of Kazakhstan, it is not favourable for households and small and medium-sized businesses to purchase solar panels, especially if they are connected to the general grid. This is due to high capital costs and a payback period.

Table 2. SWOT analysis of Kazakhstan's energy security

Tabela 2. Analiza SWOT bezpieczeństwa energetycznego Kazachstanu

Strengths	Weaknesses
1. Developed energy resource extraction industry. Kazakhstan has vast reserves of oil, gas, coal, and uranium, which makes it an important player in the global energy market. 2. Diversification of energy sources. The country is actively working on the diversification of its energy system, including the development of RES. 3. Geographical location. Kazakhstan's location in the centre of Eurasia makes it a potential transit hub for transporting energy resources. 4. Infrastructure and modernisation. The country is investing in the development of modern energy infrastructure and modernisation of the energy transmission and distribution system.	1. Dependence on oil and gas exports. High dependence on oil and gas exports makes the country vulnerable to price fluctuations in world markets. 2. Dependence on coal-fired power generation. The high share of coal-fired power generation creates difficulties in realising an efficient energy transition to RES. 3. Thermal power generation. Moving away from coal-fired generation and increasing the share of RES implies abandoning central heating and significantly increasing electricity consumption, except for the point application of geothermal technologies. 4. Inefficient use of resources. Energy efficiency in Kazakhstan remains low, resulting in inefficient use of energy resources and increased greenhouse gas emissions.
Opportunities	**Risks**
1. Development of renewable sources. Kazakhstan has great potential for RES development, which can reduce dependence on fossil fuels and assist in achieving the country's environmental goals. 2. Hydrogen energy. Hydrogen exports may become a new direction for the country, especially in light of the increasing demand in the global market and the interest of the world community as a whole. 3. Hydrogen – powered transport. Developing infrastructure for hydrogen, transport can reduce dependence on petroleum products and reduce carbon emissions.	1. Energy transition. Rejection of coal and oil products causes significant economic, political, social, and technological risks for Kazakhstan. 2. World markets and prices. Fluctuations in oil and gas prices could have a significant impact on Kazakhstan's economy and its revenues from energy exports. 3. Environmental concerns. The use of coal and oil may cause environmental problems and require additional efforts to ensure environmental safety and compliance with international regulations. 4. Geopolitical factors. Geopolitical events and conflicts in the region may affect the transit, export, and import of energy resources. 5. Technological changes. The development of new technologies and energy solutions (such as hydrogen technologies) may require a rapid response from Kazakhstan.

Source: compiled by the authors.

In general, the risks caused by the rejection of coal and oil products are not fully offset by the transition to RES and alternative energy. Industry will need high-temperature technologies, the population will be exposed to higher tariffs and fuel prices, large businesses will require large capital investments for modernisation, and heating the population in winter periods without burning fossil fuels will require a significant increase in power generation capacity (Deryaev 2024). In the long term, one of the greatest strengths of this SWOT analysis is the presence of oil and gas reserves that can be used to create an economic cushion during the energy transition. Since it is in the next 40 years that Kazakhstan's energy sector will be most vulnerable. Moreover, oil products can be used as a backup power source in case of energy shortages. In the short term, the country should focus on correcting weaknesses. It is particularly important to address energy

efficiency and grid modernisation, as the process is inevitable and the sooner it starts, the more energy savings will be possible over the next decades. Reducing grid losses and improving interconnectivity between regions of the country will enable more efficient deployment of renewable energy technologies and mitigate the effects of moving away from fossil fuels. Hydrogen can be an important factor in Kazakhstan's energy security, and its development and utilisation should be considered a priority in the country's energy policy strategy (Table 3).

Table 3. SWOT analysis of hydrogen energy in Kazakhstan

Tabela 3. Analiza SWOT energii wodorowej w Kazachstanie

Strengths	Weaknesses
1. Rich natural resources. Kazakhstan has extensive natural gas reserves, which can be used as a feedstock for blue hydrogen production if carbon capture and storage technologies are utilised. 2. Renewable energy. The country has significant potential for hydrogen production using renewable energy sources, such as solar and wind power, due to its climate and vast territory. 3. Geopolitical position. Kazakhstan has a strategic geopolitical position and can become a key player in hydrogen supply both domestically and in the global market. 4. International cooperation. Kazakhstan actively cooperates with international organisations and partners in the field of hydrogen energy development, which can facilitate the exchange of technologies and investments. 5. Existing oil and gas infrastructure. With proper modernisation, the infrastructure used to transport oil and gas could be used for hydrogen.	1. The need for infrastructure investments. Creating infrastructure for hydrogen production, storage, and transport requires significant investment. 2. Specialists. Working with hydrogen technologies requires a significant scientific base and qualified specialists. 3. Competition in the global market. The global hydrogen market is developing rapidly, and many countries have made significant progress in developing hydrogen technologies and building production facilities and infrastructure. Kazakhstan will have to compete with other hydrogen-supplying countries. 4. Low domestic demand. Domestic demand for hydrogen in Kazakhstan is currently limited, which may slow down the development of the industry. 5. Scarcity of water resources. Kazakhstan does not have access to the sea, which significantly limits the potential for hydrogen production. 6. Lack of carbon capture and storage technologies for blue hydrogen production.
Opportunities	**Risks**
1. Hydrogen export. Kazakhstan can become an exporter of green and blue hydrogen on the world market, which will create new sources of income and diversify the country's economy. 2. Reduction of carbon emissions. The development of hydrogen energy will allow Kazakhstan to reduce carbon emissions meet established environmental targets and increase the sustainability of the economy. 3. Balancing of electricity in the grid. Hydrogen can be used as a backup energy source for balancing electricity, increasing the share of RES in the country's energy mix. 4. International cooperation. Cooperation with international partners can facilitate the exchange of experience and technologies in the field of hydrogen energy. 5. Transport infrastructure development. Hydrogen can be used in the development of environmentally friendly transport infrastructure.	1. Volatility of energy prices. Dependence on prices for natural gas, oil, renewable energy sources, and hydrogen can make hydrogen energy vulnerable to changes in global energy markets. 2. Technological risks. Technical failures and safety issues can lead to serious consequences in hydrogen production and transport. 3. Political factors. Changes in the political environment and international relations can affect access to markets and resources for hydrogen energy development. 4. Creation of environmental risks. Expansion of green hydrogen production may lead to worsening water scarcity in the country.

Source: compiled by the authors.

The SWOT analysis indicates that the development of hydrogen energy in Kazakhstan has great opportunities due to the rich resources and strategic position of the country. However, achieving this goal will require overcoming several difficulties related to the need to attract investment in infrastructure and competition in the global hydrogen market. It is proposed to discuss the main elements of SWOT analysis, which have the greatest potential to affect the development of hydrogen energy in Kazakhstan. Taking into account that today the development of hydrogen energy in Kazakhstan is at the initial stage, the discussion of the analysis is focused on the prospects and risks of the new industry. The main prerequisites for hydrogen development in the country are:

- vast territories and climatic features (high insolation and strong winds) with significant potential for renewable energy generation;
- geographical position in the centre of the Eurasian continent, allowing trade in hydrogen production technologies and hydrogen itself with potentially large consumers (EU and China);
- existing infrastructure used for oil and gas transportation that could be utilised for hydrogen. At the same time, it is important to note that the country does not have access to the sea and, therefore, the possibility of sea transport of hydrogen;
- rapid growth in global demand for green hydrogen.

In general, successful implementation of the national hydrogen development policy, and overcoming technical and financial barriers will lead the country to successful hydrogen production. The most significant problem is the limited access to water, as water and electricity are the main raw materials for production. Consequently, if access to water resources for hydrogen production is significantly increased, Kazakhstan has all the prerequisites to become a leader in the industry. In addition to exports, hydrogen can also be used on the domestic market. For example, balancing electricity in the grid or hydrogen transport, which would have a favourable impact on the environment and energy security of the country.

2.4. Modelling of possible development scenarios

The main parameter of energy security is defined as access to energy resources, which is tested in terms of the three pillars of sustainable development – economic, environmental, and social. Table 4 presents the results of the modelling of possible scenarios, with further explanation of the results. The scenarios are selected based on the risks and opportunities of the SWOT analysis and key strategic documents of Kazakhstan, reflecting potential development paths for the country.

Scenario consideration:

1. The first scenario, which considers a complete phase-out of coal by 2060 in Kazakhstan, definitely has significant positive environmental effects, while causing significant damage to the economy. Moving away from coal would mean a complete restructuring of the industry and energy sector, which would require significant financial investment. At the same time,

Table 4. Modelling of possible scenarios

Tabela 4. Modelowanie możliwych scenariuszy

No.	Scenario	Economic	Environmental	Social
1	Moving away from coal	–	+	+/–
2	Development of renewable energy sources	+	+	+
3	Hydrogen for balancing	+	+	+/–
4	Green hydrogen for export	+	+/–	+/–
5	Global decline in oil and gas prices	–	–	+/–

Note: "+" – positive effect; "–" – negative effect; "+/–" – the effect is insignificant or carries equally positive and negative effects.

Source: compiled by the authors.

there is an opportunity to generate additional revenue from increased coal exports. However, the drive to reduce greenhouse gas emissions is global, and, accordingly, a global decline in coal demand is expected. In addition, this scenario assumes a significant increase in the price of heat and electricity for the population, while improving the environment, which has a dual social effect.

2. RES development implies the achievement of the established target of 50% RES share by 2050. This scenario will have a favourable impact on all three aspects under consideration. RES has a favourable economic effect, reducing the price of energy for the end consumer. Also, increasing the share of RES replaces the use of fossil fuels, which is favourable for the environment and human health. Moreover, people in remote regions of the country will be able to access energy without being connected to the grid, which will also lead to easier access to basic human needs. It is important to note that increasing the share of RES will also allow the expansion of green hydrogen production, but will increase the difficulties of balancing the electricity grid.

3. In this context, a side scenario with increased production of environmental (green or blue) hydrogen for domestic use, including as a storage tool for grid balancing, is considered. In this case, positive economic and environmental effects are expected due to the increased share of RES, the internal development of modern technologies and innovative methods to facilitate the energy transition, which could potentially lead to further development of hydrogen technologies for application in other industries and exports. At the same time, the social effects are of a point and not significant nature: an increase in jobs, and a reduction in the probability of power outages in residential buildings.

4. Similarly, large-scale production of green hydrogen will indirectly affect the lives of the country's population by creating point jobs and boosting the country's economy as a whole. In addition, as discussed in the SWOT analysis, such a development scenario may contribute to the decarbonisation of several industries, but also has a significant chance of exacerbating the risk of water scarcity in the country. It is important to note that in the case of blue hydrogen production, the economic impact will be much lower because global demand for blue hydrogen is much lower and carbon capture and storage technologies are associated with high capital costs.

5. In the event of a global decline in oil and gas prices, Kazakhstan's economy would be severely impacted by a reduction in exports and, consequently, oil production. However, there would be no significant effect on the country's energy security due to the significant fossil fuel reserves in the country. However, there will be a negative environmental effect. The slowdown in economic growth will provoke a slowdown in the energy transition.

3. Discussion

The study written above covers key aspects of Kazakhstan's energy security, including the role of hydrogen, economic implications in various energy sectors, and comparisons with global trends. It identifies the need for a diversity of energy sources, improved energy efficiency, a favourable investment environment, and risk management. The findings of the study form the basis for the strategic development of Kazakhstan's energy sector towards sustainable and balanced development.

Al-Mufachi and Shah (2022) discuss the potential of introducing the hydrogen economy into the UK energy system to reduce dependence on fossil fuels and improve the security of the energy system. The article provides an overview of current hydrogen production technologies and distribution infrastructure. The authors suggest that integrating carbon capture and sequestration systems with commercial hydrogen production technologies could reduce the present value of hydrogen production. They also note the role of hydrogen and fuel cell technologies in connecting different sectors of the economy. The authors discuss the need for government assistance to move towards decarbonisation of heat supply and suggest the use of fuel cell combined heat and power systems to improve the security of the UK energy system. However, the author's work did not consider the possible technical, economic, and social constraints that may arise when implementing these technologies, nor did they analyse in depth the potential risks and side effects of this process. Unlike the work of the researchers, the study written above analyses the potential risks and side effects of this process. Shah, the study written above takes an in-depth look at specific aspects of energy security in the context of Kazakhstan, including analyses of legislation, policy strategies, and government support measures. It also focused on energy sector strategy development, rather than only on the technical aspects of implementing specific technologies, as in the researchers' work. Nevertheless, both papers emphasize the importance of moving towards a more sustainable and secure energy system through the integration of innovative technologies and government support (Kaplun et al. 2022; Torepashovna et al. 2022).

A study by Quarton et al. (2020) presents an analysis of the role of hydrogen in energy systems and the challenges they face in the transition to low-carbon energy sources. The authors point to the potential of hydrogen as a transport fuel, heating source, energy storage, and a means of conversion to electricity and in industry. The study emphasizes that despite these prospects, hydrogen has historically played a limited role in global energy scenarios and its role in different

scenarios remains controversial. The authors highlight the mismatch between hydrogen's role in energy scenarios and the complexity of energy systems, as well as the modelling approach and data assumptions. The article offers recommendations for developing global energy scenarios that should take into account the complexity of energy systems and emerging technologies such as hydrogen. These include the use of the right modelling tools, the inclusion of relevant industries and technologies, and realistic assumptions about the data. The main advantage of the paper is in the proposed recommendations to improve the transparency and accuracy of global energy scenarios. However, the study does not offer specific solutions to overcome the inconsistencies in the role of hydrogen in energy scenarios, nor does it discuss the practical aspects of implementing these recommendations. The study above and the work of the researchers highlight hydrogen as a potential source of transport fuel and energy storage. However, the study in the previous section is more focused on specific aspects of energy security in the context of Kazakhstan, including economic implications, political strategies, and risks. Specific energy sector development strategies have also been proposed, while the work of the researchers is limited to recommendations on how to develop the energy sector. The researchers' work is limited to recommendations for developing global energy scenarios.

The work of He et al. (2020) analyses the potential of renewable hydrogen energy in the context of the energy crisis and climate change in Pakistan. The study uses a linear programming model to estimate the renewable hydrogen energy potential and its impact on electricity prices and measure the possible demand for renewable hydrogen for passenger cars. The results of the study show that Pakistan has significant wind energy potential and is capable of switching to renewable energy for its vehicles. Recommendations of the study include switching to hydrogen-fuelled passenger cars to reduce fossil fuel imports and provide clean energy sources. The study by the researchers and the study written above have a common theme of using hydrogen as a renewable energy source, however, they look at the issue in different contexts. The work of the researchers focuses on Pakistan and its potential for transitioning to renewable hydrogen energy based on linear programming modelling. Their recommendations focus on the use of hydrogen vehicles to reduce fossil fuel imports and improve the environmental situation. The study written in the previous section examined energy security in Kazakhstan, including the role of hydrogen in the context of energy sector development strategy. The economic, political, and social aspects of renewable energy deployment, including hydrogen, were analysed, and specific development strategies were proposed (Sadykov et al. 2024; Fialko et al. 1994). The study above covers energy policy and security aspects more broadly, providing recommendations for the development of the sector, and making it more applicable for decision-making at the state level. Thus, while both studies emphasize the importance of renewable energy, the current study takes a more comprehensive view of the issue in terms of energy sector development strategy in a particular country.

The study by Capurso et al. (2022) examines the prospects for hydrogen utilisation in the context of the global energy transition. The authors note the growing interest in the hydrogen economy, supported by global strategies for carbon neutrality and the transition to clean energy. The central idea of the paper is to use green hydrogen as a tool for creating flexible energy systems based on renewable energy sources. Hydrogen can be used to store excess energy and then

convert it into electricity, heat, or both, helping to reduce greenhouse gas emissions and improve the sustainability of energy systems (Prokopov et al. 1993; Deryaev 2023). The study also evaluates the advantages and disadvantages of using hydrogen in various sectors such as transport, industry, and energy. The work of the researchers also points out the difficulties of implementing hydrogen energy technologies, such as high mobility costs and difficulties in production. The study written above focused on specific aspects of energy security, emphasising the context of Kazakhstan. Not only the potential of hydrogen but also other aspects such as economic and political factors affecting the development of the energy sector were analysed. Thus, while there are similarities in considering the role of hydrogen in the energy context, this study analyses in more depth the specific challenges and opportunities in the context of a particular country, making it more relevant for practical implementation.

Common themes and conclusions are found in the research conducted in this area. These include the recognizable potential of hydrogen as a clean energy source and the identification of problems and controversies associated with its use in energy systems. In addition, recommendations are offered to improve modelling of energy systems and to develop strategies for using hydrogen as an energy resource. An equally important aspect is highlighting the role of renewable energy sources, including hydrogen, in solving energy problems at both global and regional levels.

Conclusions

This study examined the energy security of Kazakhstan and identified the potential of hydrogen as a means of ensuring sustainability. The study's principal findings include the necessity for diversification of energy sources, a reduction in reliance on oil and gas exports, enhanced energy efficiency, and the establishment of an investment-friendly environment for the development of renewable energy. These measures are crucial for mitigating economic risks and fostering a sustainable energy transition.

The findings emphasise the necessity of risk management regarding volatile energy prices and geopolitical instability. Furthermore, environmental protection is of paramount importance, particularly about the reduction of greenhouse gas emissions and the mitigation of the adverse effects of fossil fuel utilisation. While hydrogen presents a promising avenue for the decarbonisation and balancing of energy grids, it is not a panacea for achieving carbon neutrality. Consequently, further research should concentrate on the stimulation of the development of renewable energy sources, the analysis of the economic and technical feasibility of hydrogen, and the formulation of risk management strategies in response to the evolving global energy landscape.

The Authors have no conflicts of interest to declare.

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Rola wodoru w zapewnianiu bezpieczeństwa energetycznego Kazachstanu

Streszczenie

Biorąc pod uwagę aktywną politykę Kazachstanu w kierunku neutralności węglowej oraz znaczące wyzwania energetyczne i środowiskowe, badanie to jest kluczowe dla opracowania strategii zrównoważonego rozwoju systemu energetycznego Kazachstanu. Artykuł ma na celu analizę systemu energetycznego Kazachstanu, identyfikację kluczowych parametrów bezpieczeństwa energetycznego oraz zbadanie nowych możliwości, w tym roli energii wodorowej, w zapewnianiu stabilności systemu energetycznego kraju. W badaniu wykorzystano metody naukowe takie jak analiza, synteza, modelowanie oraz analiza SWOT. Oceniono dynamikę wytwarzania energii elektrycznej i produkcji ropy naftowej w Kazachstanie, wykorzystując statystyczne metody modelowania i prognozowania. Badanie określiło aktualny stan i możliwe przyszłe trendy, podkreślając wpływ dużej zależności od eksportu ropy na gospodarkę Kazachstanu oraz podatność na wahania cen na rynkach światowych. Przeprowadzono porównawczą analizę systemów energetycznych innych krajów i regionów w celu zidentyfikowania problemów i potencjalnych rozwiązań. Analizowano wpływ różnych źródeł energii, w tym węgla, ropy, gazu oraz odnawialnych źródeł energii, na środowisko i klimat. Badanie zbadało mechanizmy rynkowe wspierające odnawialne źródła energii, takie jak certyfikacja energii odnawialnej, oraz ich wpływ na dochody w sektorze. Rozważono koncepcyjne podejście do bezpieczeństwa energetycznego, analizując czynniki ekonomiczne takie jak ceny paliw i koszty kapitałowe przejścia na odnawialne źródła energii. Oceniono różne scenariusze rozwoju systemu energetycznego Kazachstanu, w tym projekcje wykorzystania energii odnawialnej i zmiany w zużyciu paliw. Wyniki tego badania mogą posłużyć jako podstawa do opracowania polityki energetycznej Kazachstanu. Zrozumienie aktualnego stanu i trendów w sektorze energetycznym pozwala na identyfikację kluczowych problemów i potencjalnych możliwości rozwoju.

Słowa kluczowe: analiza SWOT, odnawialne źródła energii, neutralność węglowa, rozwój strategii, źródła kopalne