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TOWARD HYDROGEN ECONOMY IN KAZAKHSTAN

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Abstract

The energy transition is driving governments and industries to adopt various measures to reduce their climate impacts while maintaining the stability of their economy. Hydrogen technologies are one of the central topics in the energy transition. Different nations have different stances on it. Some governments see hydrogen as a decarbonization tool or part of their energy security strategy, while some others see it as a potential export commodity. While identifying priorities for the future, Kazakhstan should clearly define the role of hydrogen in the country's long-term energy and decarbonization strategy. This work presents the first country-scale assessment of hydrogen technologies in Kazakhstan by focusing on policy, technology and economy aspects. A preliminary analysis has shown that Kazakhstan should approach hydrogen mainly as a part of its long-term decarbonization strategy. While coping with the financial risks of launching a hydrogen economy, the country can benefit from the export potential of low-carbon hydrogen in the near term. The export potential of low-carbon hydrogen in Kazakhstan is justified by its proximity to the largest hydrogen markets, huge resource base, and potentially low cost of production (in the case of blue hydrogen). Technology options for hydrogen transportation and storage for Kazakhstan are discussed in our work. The paper also identifies target hydrogen utilization areas in emission sectors regulated by Kazakhstan's Emissions Trading System.

Keywords: hydrogen roadmap, hydrogen strategy, blue hydrogen, green hydrogen, hydrogen export, metal hydrides

JEL Classification: L52, L71, Q42

Contents

1. INTRODUCTION

Kazakhstan is a major fossil energy exporter. The export of fossil fuels is strategically important–the country's foreign economy. In 2018, the country was the world's ninth-largest coal exporter, ninth-largest crude oil exporter, and 12th-largest natural gas exporter (IEA 2020). The local economy of Kazakhstan also relies heavily on fossil fuel-dominated energy generation and energy-intensive extracting and processing of natural resources (KazEnergy 2015). Nevertheless, Kazakhstan is committed to reducing the climate impacts on its economy.

The transition from fossil fuels to clean energy solutions is on the agenda of the national strategy today. In 2012, the government launched the "Kazakhstan 2050" strategy, which sets the course for long-term economic development. According to the strategy, alternative and "green" energy technologies should generate up to 50% of all energy consumed by 2050. The President of Kazakhstan, Kassym-Jomart Tokayev, sees the decarbonization of the economy as one of the main directions of the national economic course. In December 2020, at the Climate Ambition Summit, President Tokayev announced that Kazakhstan is committed to achieving carbon neutrality by 2060. Earlier, in 2016, Kazakhstan also ratified the Paris Agreement.

Many developed countries of the world are prioritizing the conservation of the environment and exploring options for the transition to a green economy. A promising direction in this joint effort is hydrogen energy. More than 40 countries around the world have developed a hydrogen strategy or roadmap. The United States, Canada, Great Britain, Germany, France, Spain, the Republic of Korea, Chile, the People's Republic of China (PRC), and India developed roadmaps as part of these initiatives (Bruce et al. 2022). Under the "Fit for 55" agreement, the EU countries are aiming for a 55% reduction in net greenhouse gas emissions by 2030. Also, under the agreement terms, the EU expects to produce up to 5.6 million tons of green hydrogen by 2030 (IRENA 2022).

The current decarbonization strategy of Kazakhstan is mainly focused on the widespread development of renewable energy sources (RES) (Strategy 'Kazakhstan 2050'). In the transition to a green economy, hydrogen energy acts as a unique bridge that can facilitate the large-scale usage of RES. Hydrogen will play an important role in balancing intermittent electricity production from RES, electricity demand, and grid stability. Also, hydrogen has the capacity to decarbonize various emissions sectors (industry, transport, energy) in Kazakhstan. For this reason, President Tokayev tasked the government to identify hydrogen energy as one of the priorities and to create a Hydrogen Energy Competence Center at KazMunayGas National Company (national oil company). Since April 2022 the center has been functioning as a research hub that investigates hydrogen energy technologies. The Competence Center conducts research on hydrogen technologies along with domestic universities and research institutes to implement projects on the production, storage, transportation and use of hydrogen, as well as CCUS solutions (KMGE 2022). This work presents the Competence Center's preliminary findings in exploring opportunities for the future hydrogen economy in Kazakhstan.

The topic of hydrogen energy is new not only for Kazakhstan but also for Central Asia. The National Energy Report 2021 from KazEnergy contains a short review of the possibilities of hydrogen energy in Kazakhstan (KazEnergy 2021). Nevertheless, there has been no systematic study covering the potential for a full chain of hydrogen technologies in the Central Asia region. Our work aims to provide the first country-level assessment of hydrogen technologies in Kazakhstan covering various policy, technology, and economy aspects:

1. Section 2 identifies the main drivers, which can affect the adoption of the hydrogen economy in Kazakhstan.
2. Section 3 analyzes opportunities for the hydrogen value chain in Kazakhstan (production, storage, transportation, and utilization) covering various technical and economic aspects.
3. The final section provides our preliminary conclusions, recommendations, and limitations for the development of a hydrogen economy in Kazakhstan.

2. WHY DOES KAZAKHSTAN NEED HYDROGEN?

A recent review of various national hydrogen strategies reveals different stances adopted by countries on the future hydrogen economy (IEA 2021). Three main reasons are driving different nations to pursue the development of a hydrogen economy: **(1) decarbonization**, **(2) export potential**, and **(3) energy security**. Below we discuss which of these drivers could work in Kazakhstan while establishing a hydrogen economy.

2.1 Decarbonization in Kazakhstan

Kazakhstan first expressed its interest in regulating GHG emissions in 1999 by signing the Kyoto Agreement. The terms of the Kyoto Agreement laid the foundation for the development of the Kazakhstan Emissions Trading System (ETS), which regulates GHG emissions with market mechanisms such as "cap and trade." The approval of the "Green Economy Concept" in 2013, commitment to achieving the Sustainable Development Goals in 2015, and ratification of the Paris Agreement in 2016 only bolstered the commitment of Kazakhstan to GHG emission reduction by introducing more ambitious goals in this regard (Table 1). Both conditional and unconditional targets (328 and 290 Mt CO_2 eq.) set by the Paris Agreement have already been exceeded in 2014 and 2016, respectively (Abuov, Seisenbayev, and Lee 2020). The President's recent announcement about the carbon-neutrality goal of Kazakhstan by 2060 requires substantial work to be done on the regulation of each GHG emission sector (UN PAGE 2021).

Table 1: GHG Emission Targets of Kazakhstan

Year	GHG Emissions, Mt CO_2 eq.	Regulating Document
1990 (base year)	386	Not regulated
2030	328 (unconditional target) 290 (conditional target)	Paris Agreement
2060	0	Doctrine of carbon neutrality (not approved yet)

General approaches to emission reduction were outlined in the Green Economy Concept of 2013, which revealed low efficiency and high GHG emissions in the energy system of Kazakhstan compared to developed countries (Kazakhstan Government 2013). The Concept proposed approaches such as an increase in energy efficiency, modernization of existing power plants, deployment of RES, a decrease in CO_2 emissions, and increased use of natural gas (gasification) to establish a green economy. Compared to the last decade, Kazakhstan's energy system has seen some progress by mainly relying on RES deployment and an increased share of gasification. The share of RES reached around 3% in 2020. Gasification of regions reached 53% of the population. The share of gas-fired thermal plants reached 20%, as stated in the Concept of 2013 (KazEnergy 2021).

In the coming decade, Kazakhstan will have to challenge itself to achieve even more ambitious decarbonization goals. Approaches suggested by the Concept of 2013 are not sufficient to reach carbon neutrality given the further increase in energy demand of the country. The decarbonization capacity of RES technologies is limited for so-called "hard-to-abate" sectors (heavy industry and transport) (IEA 2020). The GHG emissions from "hard-to-abate" sectors can be reduced by low-carbon technologies, such as hydrogen and carbon capture utilization and sequestration (CCUS), which are not featured in the Green Economy Concept of 2013. Although the current energy and climate policy of the country does not recognize the importance of hydrogen, the new decarbonization policy of Kazakhstan – the Doctrine of Carbon Neutrality – does. The Doctrine is in the development stage and has not been approved yet. The first draft for public consultation appeared in 2021, covering hydrogen-related decarbonization solutions (UN PAGE 2021). Nevertheless, the country needs a dedicated hydrogen strategy or roadmap to accelerate the transition from a hydrocarbon economy to a hydrogen economy. The hydrogen roadmap should provide confidence to the interested stakeholders along the hydrogen value chain.

2.2 Carbon Regulation and Hydrogen

Carbon regulation is the policy instrument of decarbonization and it presents a significant driver for the hydrogen economy. Carbon regulation exists in many jurisdictions of the world, and Kazakhstan is not an exception. The hydrogen industry in Kazakhstan can be affected by both internal and foreign carbon regulations.

Internally, carbon emissions in the country are regulated by the Emissions Trading System (ETS), which is Kazakhstan's analog of the EU ETS. The ETS in Kazakhstan was pre-launched in 2013 in the testing mode (Jasyl Damu JSC 2021). The time period between 2013 and 2018 was used to identify and fix regulatory and technical issues, namely a trading mechanism was defined and the Environmental Code was improved. The ETS was fully launched on 1 January 2018. Sectors involved in the ETS include the power sector, metallurgy, oil and gas, mining, the chemical industry, and production of construction materials (lime, cement, brick, and gypsum production). The National Allocation Plan for 2018–2020 was set with a total quota for GHG emissions of 485,909,138 t CO_2 (Ministry of Justice 2017). As for 2018–2020, the ETS covers operators with 225 units with each having more than 20,000 t CO_2/year (ICAP 2021). Table 2 demonstrates that power generation is the key CO_2 emitter, while metallurgy and oil and gas industries are the second and third major emitters, respectively. All three sectors can be decarbonized to some extent by applying hydrogen technologies. A more detailed analysis of hydrogen utilization in each ETS-regulated sector can be found in Section 3.3. Currently, CO_2 prices in Kazakhstan are low (1.1 USD/t CO_2) to drive the implementation of decarbonization technologies including hydrogen (ICAP 2021).

Unlike the internal carbon regulation of Kazakhstan, foreign carbon regulation is strong enough to provide incentives for industries to adopt various decarbonization technologies. For instance, carbon prices in EU ETS reached 80 USD/t CO_2 in 2021 (Reuters 2022). Recently, EU members also agreed to launch the Carbon Border Adjustment Mechanism (CBAM) in 2023. The Mechanism is a key aspect of the EU's broader "Fit for 55" package, which aims to reduce 55% of the EU's net greenhouse gas (GHG) emissions by 2030 (EY 2021). The CBAM is directly related to the EU ETS and is its future replacement. After the Mechanism starts working in 2023, a transitional period will last until the end of 2025, during which no carbon tax will be charged. The transitional period will oblige importers to report the carbon footprint of imported products. After 2026, the payment of the carbon footprint will be made by purchasing emission certificates at a price set during a weekly auction. The CBAM industry coverage is limited during the initial stages. Now it covers products from ferrous metallurgy, aluminum, cement, nitrogen fertilizers, and power, which together represent about 5% of EU imports. The CBAM tax will get stronger by adding new products to the list and by increasing carbon prices. The CBAM presents financial risks for Kazakhstan's exporters trading the above-mentioned goods in the EU territory. Metallurgy in Kazakhstan is one of the goods exported to the EU that may start losing part of its revenue due to the CBAM tax from 2026 (LSM.KZ 2021). The utilization of low-carbon hydrogen in Kazakhstan's industries might tackle the negative consequences of the CBAM.

Table 2: Distribution of the CO_2 Cap from the National Allocation Plan for 2018–2020

Regulated Industry	Number of Units	Quotas for 2018–2020, Tons of CO_2
Power generation	94	269,954,543
Oil and gas	67	68,564,839
Mining	24	30,642,622
Metallurgy	20	91,153,819
Chemical	6	4,686,201
Production of construction materials	14	20,907,114
Total	**225**	**485,909,138**

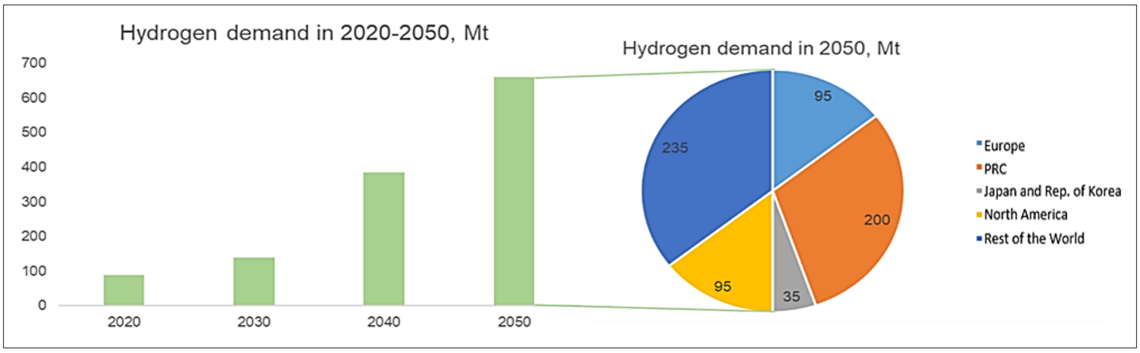
Source: Ministry of Justice 2017.

2.3 Hydrogen as an Export Commodity

A review of the current hydrogen market and projection of future demand was published in a recent study by the Hydrogen Council and McKinsey (2021a). In 2020, 90 Mt of hydrogen was produced mainly from natural gas followed by coal and by-products. The hydrogen market will reach 660 Mt in 2050. Some 45% of the market is represented by the PRC and Europe, which are expected to consume 200 Mt and 95 Mt of hydrogen, respectively (Figure 1). More and more giga-scale hydrogen projects have been announced in the world recently, but their capacity is unable to fulfill the demand for hydrogen that is essential for reaching the net-zero goal. In this regard, Kazakhstan's unique location between the two largest hydrogen markets of the PRC and the EU can be a key factor for the further development of the hydrogen industry with a priority for low-carbon hydrogen (green/blue) to succeed even in markets with strong carbon regulation.

Another driver for hydrogen industry development is energy security. The instability of the gas and oil market caused by the geopolitical situation has prioritized energy security over the energy transition. For instance, Germany has recently adopted an emergency law that allows the launching of coal-fired plants to fulfill the electricity demand until March 2024 (Robertson 2022). For energy-importing countries, hydrogen can be a new energy source with diversified local production and import options. In the case of Kazakhstan, its vast amount of renewable and fossil fuel resources indicates that the country can meet local energy consumption for a long period. Currently, hydrogen does not have a big role in the energy security strategy of the country. Kazakhstan can help other countries to address their energy security concerns by exporting both traditional and alternative energy sources like blue/green hydrogen.

Figure 1: Hydrogen Demand in 2020–2050



Source: Hydrogen Council and McKinsey 2021b.

3. ESTABLISHING A HYDROGEN VALUE CHAIN IN KAZAKHSTAN

3.1 Low-Carbon Hydrogen Production

Subsections 3.1.1 and 3.1.2 discuss the availability of fossil fuel resources and renewable power supply for blue hydrogen and green hydrogen production, respectively. Subsection 3.1.3 explores carbon intensity, water footprint, and cost aspects of low-carbon hydrogen production technologies in Kazakhstan. A summary of our analysis is provided in Table 3.

3.1.1 Blue Hydrogen

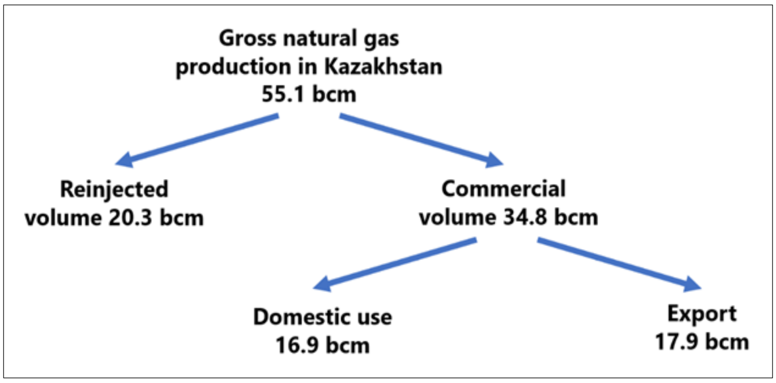
Blue hydrogen from natural gas or associated petroleum gas (APG)

The main feedstock resources for blue hydrogen are natural gas, associated petroleum gas (APG), and coal. Syngas obtained from steam methane reforming (SMR)/ autothermal reforming (ATR) of natural gas or coal gasification can produce syngas, which contains hydrogen and CO. Further processing in water-gas shift reactions results in CO_2 emissions. The CO_2 from syngas processing should be captured and stored for hydrogen to be considered blue.

Kazakhstan positions itself as an energy exporter with huge natural gas, oil, and coal reserves. According to BP 2021, Kazakhstan holds the 16th-largest hydrocarbon gas reserves in the world, which represents 1.2% of global reserves with the vast majority being located in the western part of the country and few gas fields located in the southern part (KazEnergy 2021). Nevertheless, the country might have difficulties in having available feedstock natural gas for large-scale blue hydrogen production.

Gross gas production in the country reached 55.1 bcm in 2020, with 34.8 bcm and 20.3 bcm being commercial and reinjected volume, respectively (Figure 1). Commercial volume was used domestically and exported to other countries. The country sees natural gas as an opportunity to decrease the carbon intensity of its economy, thus Kazakhstan has been gradually increasing domestic gas consumption since 1999 and has already started to face shortages. Recently the government announced its plan to divert 2 bcm of the export volume into the domestic gas market (Reuters 2022). Exported volume also cannot be considered for blue hydrogen production with current gas prices, since returns from selling gas are probably higher than from converting it into hydrogen and selling it (Isidore 2022).

Figure 2: Natural Gas Production in Kazakhstan (2020)



Source: KazEnergy 2021.

Reinjected volume (20.3 bcm) is tightly used mainly for the reinjection needs of the three largest hydrogen reservoirs, namely Karachaganak, Tengiz, and Kashagan, which produced 79% of Kazakhstan's commercial natural gas in 2020 (KazEnergy 2021). Each of the three fields has production plans for the next several decades to increase or maintain oil production, thus reinjected gas volume cannot be used if they cannot be replaced with some other gas. One option would be to add new SMR units to the existing gas processing facilities of three large oil fields to obtain syngas from natural gas and APG. Syngas should be later processed into hydrogen and CO_2 streams. CO_2 used in enhanced oil recovery (EOR) could effectively replace the currently reinjected gas if captured in sufficient volume. The blue hydrogen project with a similar concept is operated by Air Products in Port Arthur, Texas. Smaller oil and gas fields can also consider blue hydrogen production if they use the cluster approach by sharing gas processing facilities and gas pipelines. In general, the following blue hydrogen production options for Kazakhstan should be studied in detail:

- Blue hydrogen production potential from the three largest reservoirs (replacing reinjected gas with CO_2 emitted from H_2 production)
- Cluster option for smaller oil fields to process their APG in shared infrastructure (sharing gas processing facility)
- Integrate utilization of emitted CO_2 with enhanced oil production (EOR) and chemical complexes (urea, methanol production, beverage industry, etc).

Blue hydrogen from coal

The gasification of coal with subsequent CO_2 capture can result in blue hydrogen. Kazakhstan is considered the tenth-largest coal resource holder in the world with 29.4 billion tons across 49 deposits, with major reserves being located in the north and central parts of Kazakhstan (Karagandy, Ekibastuz, and Turgay coal basins). Energy consumed in Kazakhstan was primarily generated by coal and accounted for 56% in 2020 (KazEnergy 2021). IHS Markit estimates that domestic coal demand will decrease by 2030 and 2040 to 51% and 42%, respectively (KazEnergy 2021). The dropping share of coal stems from the development of gasification infrastructure across the country, as the country plans to decrease the carbon intensity of its economy by using natural gas. Nevertheless, coal will remain an affordable and indispensable fuel in Kazakhstan for the next several decades.

GHG emissions from traditional combustion technologies are responsible for 171.63 million tons of CO_2 eq., which represents ~59% of GHG emissions in energy and industry (Andrew 2021). The gasification of coal to obtain hydrogen gas from syngas with subsequent capture of CO_2 can provide a clean energy solution for both energy and industry uses. Commercial coal gasification facilities operate in the US, the PRC, and Australia (CoalAge 2021). Coal gasification technology in Kazakhstan has not reached the commercial stage and remains in the R&D stage with several projects related to fixed-bed, plasma, and underground coal gasification (Tokmurzin et al. 2019; Messerle, Ustimenko, Lavrichshev 2021; Martemyanov et al. 2021).

Unlike natural gas, coal in Kazakhstan has no resource shortage problem. Blue hydrogen production will not compete with current coal use, and thus coal could provide feedstock for the longer term. A problem may arise with subsequent utilization and storage of CO_2 during blue hydrogen production. Identified CO_2 storage and potential utilization areas are located in the western part of Kazakhstan, while the geography of coal reserves is mainly central and northern parts of the country (Abuov, Seisenbayev, and Lee 2020). Without nearby CO_2 storage and utilization, the cost of CO_2 transportation can provide a serious hurdle for coal gasification in Kazakhstan. Thus, CO_2 storage and utilization options need to be explored in nearby geological formations and industries (North and Central Kazakhstan).

3.1.2 Green Hydrogen

Hydrogen production from electrolyzers can be classified as green only if the electricity comes from renewable energy sources (RES). According to the new Environmental Code (2021) of Kazakhstan, solar, wind, hydro, biomass, and waste energy are classified as RES (Table 2). Kazakhstan has been gradually increasing the share of RES in the country's energy mix. The share of wind and solar power has reached 1.47 GW (6.2%) out of 23.6 GW of the total installed capacity in the country (KazEnergy 2021). The government plans to increase RES capacity to 4.5 GW by 2028 (Ministry of Energy 2022). According to the Green Economy Concept of 2013, power generation by RES is planned to reach 50% of the total power output by 2050. Nevertheless, we expect that existing and near-future RES capacity will be in tight use due to the power shortage in the country (south region), thus existing and near-future RES capacity is insufficient for large-scale green hydrogen production. But with the planned 50% power generation from RES in 2050, the risk of mismatch between generated and consumed electricity grows. Due to the volatile nature of RES power generation, some part of generated power will be surplus or "lost." In the longer term, green hydrogen production developers can benefit from excess RES power during power surplus seasons of the year, although surplus power will not be stable enough throughout the year to sustain the continuous operation of electrolyzers (IEA 2017). In the near term, it makes more sense to focus on the unrealized RES potential of Kazakhstan by building an off-grid renewable energy supply for electrolyzers.

Generally, the southern part of the country has an advantage over the northern for both solar and wind project potential for future RES projects. Currently, the majority of RES projects are based in southern Kazakhstan. Recently, German-Swedish company Svevind signed an MoU with Kazakhstan's government to build a green hydrogen production facility in the Mangystau region, which will be powered by wind and solar energy with a combined output of 45 GW (Energy Connects 2021). The project is in the

Pre-FEED stage today. If approved, the construction of wind and solar farms with a capacity of 45 GW will be commissioned between 2030 and 2032. Ultimately, 2 million ton/year of green hydrogen will be produced. However, as the electrolysis relies on the water to extract hydrogen, local challenges (especially in the Caspian Sea) with water supply should be strictly considered. More details on the water footprint of hydrogen production are covered in Section 3.1.3. Another issue would be the proper management of brine resulting from large-scale desalination of water. Disposing effluent brine back to the water body might have negative consequences for the marine environment.

Table 3: RES Plants in Kazakhstan

#	Type of Renewable Energy Source	Number of Plants
1	Hydro	47
2	Solar	45
3	Wind	29
4	Biogas	1

Source: Ministry of Energy RoK 2022.

From a renewable power supply perspective, future developers of green hydrogen production projects should consider the following:

- Near-term green hydrogen production projects should rely on a dedicated power supply, as current RES capacity is tightly used to cover local electricity demand.
- In the longer term, when the RES share reaches 50%, power surplus might be available for green hydrogen production during seasonal peak power generation by RES.

3.1.3 Carbon Intensity, Water Footprint, and Cost of Low-Carbon Hydrogen Production

Carbon intensity is the main trading feature of hydrogen in the energy transition era. The carbon intensity of natural gas-based and coal-based blue hydrogen is around 9 kg CO_2 eq/kg H_2 and 20 kg CO_2 eq/kg H_2, respectively (Table 4). Applying CCUS technology with a 90% capture rate can bring down numbers to 1 kg CO_2 eq./kg H_2 and 2 kg CO_2 eq./kg H_2 for natural gas-based and coal-based blue hydrogen, respectively (IEA 2020). However, data provided by IEA represent the global average and these numbers cannot exactly describe the carbon intensity of blue hydrogen in Kazakhstan. Two factors drive GHG emissions of natural gas-based blue hydrogen: (1) the carbon intensity of natural gas (especially methane emissions), and (2) the CO_2 capture rate (Bauer et al. 2022). Kazakhstan has one of the lowest flaring rates from APG (1.2%) in the world, thus it can have an even lower low-carbon intensity of blue hydrogen than the global estimate of IEA (KazEnergy 2021). The carbon intensity of green hydrogen depends on the source of electricity feeding electrolyzers. As long as the power source is renewable (wind, solar, etc.), green hydrogen has no GHG emissions.

Water is another important resource in hydrogen production. A recent study shows that green hydrogen production requires about 9 liters of water to produce 1 kg of hydrogen. In the case of the PEM electrolyzer, this number goes up to 18 kg per kg of hydrogen (Table 4). The water footprint of the natural gas-based hydrogen process varies between 13 and 18 kg of water per kg of hydrogen. The highest water footprint with 40–85 kg water/kg hydrogen belongs to low-carbon hydrogen obtained from coal gasification (Hydrogen Council 2021). Kazakhstan has eight water basins, seven of which lie in transboundary territories. Some 45% of annually renewable resources of surface water come from the territory of neighboring countries (Senate 2019). Given the impending challenge of water scarcity in the country, careful analysis of water balance must be carried out by clearly outlining how much water would be consumed by each sector. Developing hydrogen energy in the country should not prioritize energy transition at the cost of water security.

Currently, the cheapest hydrogen production pathway is gray with USD1–1.9/kg H_2 (IEA 2020). Adding CCUS unit to SMR and coal gasification results in blue hydrogen cost ranges of USD1.4–2.4 and 2.0–2.2/kg H_2, respectively (Table 4). The cost driver of natural gas-based blue hydrogen is the cost of natural gas feedstock. Having one of the lowest prices of natural gas globally, Kazakhstan could have one of the lowest costs for blue hydrogen production. The coal-based blue hydrogen cost is mostly driven by Capex and Opex. The CO_2 capture rate has a substantial impact on both types of blue hydrogen, with high capture rates resulting in high production costs. The cost of green hydrogen production is the highest, ranging between USD2.5 and 6.6/t H_2. The main cost drivers for green hydrogen are electricity cost, load factor, electrolyzer efficiency, and Capex with the latter being the main driver. Decreasing the Capex of green hydrogen in the longer term requires establishing local manufacturing of low-carbon technology involved in the supply chain of green hydrogen production (electrolyzers, wind turbines, solar panels, etc.). Lastly, high carbon prices in the future can increase the competitiveness of both blue and green hydrogen types significantly.

Table 4: Gray, Blue, and Green Hydrogen Production

Hydrogen Color	Gray Hydrogen		Blue Hydrogen		Green Hydrogen
Production technology	SMR	Coal gasification	SMR	Coal gasification	Water electrolysis
Resources estimate for Kazakhstan	Tight natural gas supply, but resource base can be expanded	Abundant coal resources	Tight natural gas supply, but resource base can be expanded	Abundant coal resources	Abundant renewable energy resources, but installed RES capacity is limited
Carbon intensity (kg CO_2 eq/kg H_2)**	9	20	1	2	0
Water footprint (kg water/kg H_2)***	14–17	41–86	13–17	41–86	9–18
Production cost (USD/kg H_2)*	1.0–1.9	1.6–1.8	1.4–2.4	2.0–2.2	2.5–6.6

Notes: * Global estimate from IEA 2020.
** Hydrogen Council 2020.

3.2 Hydrogen Storage and Transportation

Since hydrogen is considered one of the main instruments for hitting the goals of decarbonization, it will be massively used in the different sectors of the economy. Hydrogen can be transported in different phases (gas, liquid, and solid). Operating conditions such as temperature, pressure, gravimetric capacity, etc. form the cost of hydrogen storage and transportation. It was suggested that the most cost-effective option for hydrogen distribution will be a pipeline system for distances below 1,500 km. For longer distances, shipping is the most efficient alternative way (IEA 2019). However, shipping hydrogen is not applicable in Kazakhstan today as the country is in a different position with limited access to the sea/ocean but with sufficient facilities to connect Europe and Asia via continental territory.

Technical and related economic parameters of hydrogen storage and transportation were discussed for different phases such as liquid, gaseous, and solid (Table 5 and Table 6). The study first looks at using existing pipelines to blend hydrogen with natural gas. This is followed by a discussion on hydrogen storage and delivery in liquid form. Finally, it examines the application of metal hydrides to store and distribute hydrogen.

3.2.1 Hydrogen Storage and Transportation in Gaseous Form

Currently, hydrogen is stored in liquefied and compressed forms, which are mostly used on sites. Hydrogen storage in gaseous form is suitable for small-scale storage where gaseous hydrogen is achieved by compressing it up to 350–700 bar (Table 5). Hydrogen distribution via pipelines is a well-known practice. The length of existing hydrogen pipelines is around 5,000 km where hydrogen is mostly utilized as a chemical feedstock (IEA 2019, 2021). Repurposing existing natural gas pipelines into a pure hydrogen network needs proper engineering solutions (Cerniauskas 2020). Existing pipelines can accommodate around 1% of hydrogen and natural gas mix without engineering modifications. Many countries have limited amounts of hydrogen injection in natural gas networks for safety reasons. Currently, there are several pilot projects and studies developing pipeline systems for blending (Wu et al. 2022).

The annual report of the NC "QazaqGaz" (previous name NC "KazTransGaz") for 2020 states that the total length of the natural gas pipelines is more than 20,000 kilometers, with a piping capacity of 227.9 bln.m^3 per annum (Annual report 2020). In the last decade, due to intensive gasification, around 53% of the population has been able to use natural gas in their home. However, the country is facing low investment in the oil and gas industry today, which could lead to a decrease in the volume of natural gas in the future. To increase a resource base, hydrogen could be blended with natural gas and delivered by the existing pipeline system. Pipelines are likely to be a cost-effective option not only for local hydrogen distribution but also for exports for distances of less than 5,000 km as there is an increase in the cost of engineering services (Table 6). Overall, the blending of hydrogen with natural gas could be considered a transitional step toward the deployment of hydrogen energy and broadening a resource base for the country. The pipelined distribution of hydrogen could also boost the demand in the hydrogen market.

3.2.2 Hydrogen Storage and Transportation in Liquid Form

Hydrogen in the liquid phase can be achieved at temperatures below –253°C by reducing its volume by 800 times compared with gaseous hydrogen (Table 5). Liquid hydrogen is transported in super-insulated, cryogenic tankers or trucks for longer distances (Ren et al. 2017). Currently available technologies for liquid hydrogen storage and transportation have several drawbacks, including the need to maintain cryogenic conditions resulting in high energy consumption of more than 30% of the energy content of the hydrogen (Dagdougui et al. 2018). Another issue with liquid hydrogen is boil-off (Aziz, Oda, and Kashiwagi 2018). Issues of liquid hydrogen transportation can be handled by incorporating hydrogen into large molecules such as liquid organic hydrogen carriers (LOHCs) and ammonia. LOHCs include methylcyclohexane (MCH) and toluene (Chiyoda corporation). It is suggested that over long distances, hydrogen transportation such as LOHCs and ammonia presents cost-effective solutions, especially overseas (IEA 2019).

Table 5: Hydrogen Storage Methods

Phase	Gas	Liquid			Solid		
Storage type	Gaseous hydrogen	Liquid hydrogen	Ammonia	LOHC (MCH)	Intermetallic hydrides	Complex hydrides	Porous materials
Method	Compressed	Cryogenic	Chemical	Chemical	Chemical	Chemical	Chemical
Gravimetric capacity*, wt %	13	100	17.8	6.16	0.91–3.3	2.96–18.5	< 20
Volumetric capacity*, ($kg\text{-}H_2/m^3$)	< 40	70.8	121	47	150	147	< 20
Temperature, ℃	r.t.	–253	25	240	r.t.	> 100	varies
Pressure, bar	350–700	1	10	10	1	1	100
Advantages	• Good fit for small-scale applications	• High volumetric and gravimetric capacity	• Cheap • Existing technology	• No cooling • Existing technology	• High volumetric capacity • Safe • Reversible	• High volumetric capacity • Safety	• Reversible • Fast cycle life
Disadvantages	• Low volumetric capacity • High pressures	• Energy-intensive • Boil-off risk	• Toxic • Requires conversion	• Desorption at high temperature • Requires conversion	• Low gravimetric capacity	• Low gravimetric capacity • Low reversibility	• Clustering problem • Weak interaction with hydrogen

Note: * Zuttel (2003), Ley et al. 2014; Niaz, Manzoor, and Pandith (2015); Bellosta von Colbe et al. (2019); Aziz, Oda, and Kashiwagi (2018).

As Kazakhstan is a landlocked country, sea and river shipping are not a widespread type of transportation. The marine transport industry is represented on the Caspian Sea by the ports of Aktau, Kuryk, and Bautino. Transit shipping in the Caspian Sea includes routes from Aktau to Baku (475 km), Turkmenbashi (550 km) and Bandar Anzeli (700 km) (Table 6) (Overview CAREC Program 2021). Currently, shipping on the Trans-Caspian International Transport Route (TITR), known as the Middle Corridor, has increased by 41% (MIID 2022). Nevertheless, the transport capacity of Kazakhstan ports is limited currently. Also, hydrogen transport via the Caspian Sea does not reach target export destinations directly but only transit countries such as Azerbaijan, the Russian Federation, and Iran. Further, it needs to be transported via terrestrial transportation modes such as pipeline, railway, or truck.

3.2.3 Hydrogen Storage and Transportation in Solid Form

Hydrogen can also be incorporated into solid-phase materials such as metal hydrides, complex hydrides, and porous materials. Hydrogen adsorbed in metal alloys can offer a safe and high volumetric storage capacity under standard conditions. Nowadays, this method of storage and transportation is in its demonstration stage and is used by several companies (Bellosta von Colbe et al. 2019). The practical application of metal hydrides requires a good kinetic rate of hydrogen adsorption/desorption and higher gravimetric capacity. Despite having relatively low gravimetric capacity, hydrides can achieve a high volumetric capacity of hydrogen storage with up to 150 kg H_2/m^3 (Table 5). Carrying high-mass and low-volume cargo is particularly suitable for railway transportation.

There has been a study suggesting hydrogen storage and transportation by Ti-based alloys in Kazakhstan via railway (Zholdayakova et al. 2020). This study shows that Kazakhstan has reserves of titanium, chrome, manganese, and iron ores that could be used to develop new hydrogen storage alloys at a much more affordable price. Unlike shipping, railway transportation is prevalent and much more affordable for landlocked countries (Table 6). Kazakhstan has become the most important partner in the “One Belt, One Road” program to connect Europe and Asia, which promises an expansion in the railway transportation capacity of the country. Developing optimum metal hydride technology can enable large-scale transportation of hydrogen from Kazakhstan to the largest hydrogen markets such as the EU and the PRC.

Table 6: Hydrogen Transportation in Kazakhstan

Transportation Type	Distance, km	Cost*, USD/kgH_2	Phase
Pipelines	1000–5000	0.6–3.3	Gas
Railways	500–5000	Not evaluated	Gas, liquid, and solid
Trucking	< 1000	0.2–3.3**	Gas, liquid, and solid
Shipping	500–1000	< 2.2	Liquid

Notes: * Costs include conversion and moving costs (based on Figures 28 and 29 in IEA 2019).
** The cost of tracking does not include hydrogen distribution in the solid phase.

3.3 Hydrogen Utilization

Hydrogen can decarbonize many emission sectors, however current hydrogen utilization costs cannot compete with the costs of conventional carbon-intensive technologies. The role of carbon regulation is vital in making hydrogen technologies attractive to investors. Thus, we have categorized hydrogen utilization in the context of ETS in Kazakhstan. The average of regulated emissions in 2018–2020 constitutes around 43% of the total GHG emissions in the country in 2019 (KazEnergy 2021). In the subsections below, we have categorized each emission sector as existing, near-term, or long-term hydrogen utilization sectors. Target hydrogen utilization areas and decarbonization effects were identified in each sector (Table 7). The decarbonization effect implies the extent of the expected carbon emissions reduction in a particular hydrogen utilization area.

3.3.1 Existing Hydrogen Utilization Areas

Currently, gray hydrogen is utilized in regulated oil and gas and chemical sectors, which are responsible for 5.2% and 0.5% of the total GHG emissions in the country. Two refineries and one ammonia plant in Kazakhstan produce gray hydrogen from natural gas via the SMR process and utilize it in their own technological processes (hydrocracking in the refineries, feedstock for the "Haber-Bosch" process in the ammonia plant). From a decarbonization perspective, an obvious step would be adding CO_2 capture units to obtain blue hydrogen in the SMR units of the refineries and the ammonia plant. The decarbonization effects of blue hydrogen use in refineries and ammonia will be different due to the different shares of SMR emissions in the total GHG emissions of the two facility types. Some 30–40 % of cradle-to-plant-gate GHG emissions in the ammonia plant come from the carbon intensity of the feedstock, which is mainly natural gas used for hydrogen production (Hydrogen Council and McKinsey 2021a). Thus, opting for low-carbon hydrogen can result in a significant reduction of GHG emissions in the ammonia plant. In a typical refinery, the SMR unit is responsible for around 11% of GHG emissions; thus, using blue or green hydrogen in refineries will not significantly reduce the carbon footprint of refinery products (Sunny et al. 2022). Nevertheless, refineries and ammonia plants are the first targets for low-carbon hydrogen utilization in Kazakhstan, as they are already utilizing hydrogen. While switching to low-carbon hydrogen utilization in refineries and ammonia plants, it is necessary to dispose of or utilize emitted CO_2. CO_2 could be directed to nearby oil fields experiencing a decline in pressure (CO_2-EOR). Another option is integration with future petrochemical and chemical complexes (methanol production, urea production, beverage industry, etc.).

3.3.2 Near-Term Hydrogen Utilization Areas

Regulated GHG emissions from metallurgy are responsible for 8% of the total GHG emissions in Kazakhstan. The decarbonization of the iron and steel sector can be achieved by switching away from coal to electricity or natural gas, especially by using an electric arc furnace (EAF) to purify metal scraps or direct reduced iron (DRI) into steel (IEA 2021). EAF steel has 14 times less carbon intensity than steel obtained from an integrated blast furnace (BF) and basic oxygen furnace (BOF), which mainly rely on coal combustion (Hydrogen Council and McKinsey 2021b). Feedstock for an EAF can be metal scraps or direct reduced iron (DRI). The reduction of iron oxides into metallic iron for DRI can be achieved by using hydrogen as a reductant gas. A 100% hydrogen-based steel production for full decarbonization would be difficult for the industry, but injecting 25% hydrogen can partially decarbonize the steel sector without major modifications in steel plants (IEA 2018). Kazakhstan produces steel from both BOF and EAF processes. Metallurgy products will be first subjected to the CBAM from 2026 if exported to Europe (EY 2022). Utilizing hydrogen for the manufacturing of DRI-EAF steel may help to avoid high carbon taxes incurred by the CBAM.

3.3.3 Long-term Utilization Areas

Around 25.7% of GHG emissions in Kazakhstan belong to the ETS-regulated power and heat sectors. GHG emissions in the power and heat sector are dominated by coal, which produced 56% of the energy consumed in Kazakhstan as of 2020 (KazEnergy 2021). Currently, the government plans to reduce GHG emissions in this sector by increasing the share of natural gas in the energy mix of the country. Replacing coal with natural gas can result in twice fewer GHG emissions. The carbon intensity of heat and power would be further reduced by blending hydrogen with natural gas in the longer term. Hydrogen blend does not require significant infrastructure upgrades and can be operated under safe blending limits. Current natural gas pipeline networks could cope with a 10% hydrogen blend, but the capacity of end users to consume hydrogen blend is rather limited. Current gas turbines would handle a 1% blend, which could be increased to 5–15 % after some modifications (IEA 2017). The IEA (2018) estimated that a 20% hydrogen blend in the European natural gas network would reduce GHG emissions by 7% (Table 7). The hydrogen blend would also alleviate the impending issues of the natural gas deficit in Kazakhstan.

Using electricity power to obtain hydrogen and converting hydrogen back to power would result in low efficiency. However, hydrogen is interesting in storing excess energy that may result during peak power generation of RES. Unlike fossil fuels, RES power fluctuates according to the season, weather conditions, and rotation of the Earth. As the share of RES in the energy mix increases, the risk of mismatch between generated and consumed power will increase as well. According to the Green Economy Concept of Kazakhstan, the RES electricity generation will reach 50% in 2050 (Kazakhstan Government 2013). A 50% share of RES can worsen the existing problem of the Kazakhstan power system's balancing and stability. The country has a shortage of flexible capacity (KazEnergy 2021). Hydrogen can provide flexibility to Kazakhstan's electricity grid by storing excess RES energy for a seasonal period. This would provide a long-term balance between energy production and consumption.

GHG emissions from the transport sector are not regulated by the ETS and they represent 7% of emissions in Kazakhstan (Forbes 2021). Around 80% of transport emissions belong to vehicles, which are mostly represented by cars over ten years old running on diesel. Diesel engines are also responsible for the low air quality in many of Kazakhstan's cities (OECD 2017). Existing decarbonization solutions for the transport sector include fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs). FCEVs run on hydrogen. The competitiveness of FCEVs increases over long-range distances. Thus, demand for hydrogen will be mainly from medium-range vehicles, transit buses, medium-duty trucks, heavy-duty trucks, cargo vans, and shuttle buses (Global Commercial Drive to Zero Program 2022). Hydrogen utilization in the transport sector of Kazakhstan is possible only after establishing hydrogen infrastructure (hydrogen station), which might be a reality in longer-term perspectives.

Table 7: Hydrogen Utilization Perspectives in GHG Emission-Regulated Sectors

Regulated Sectors	Emissions Share*, %	Target Hydrogen Utilization Area	Decarbonization Effect from Hydrogen Utilization	Perspectives in Kazakhstan
Metallurgy	8	• Direct reduction in iron production	Major	Near-term
Construction materials	1.9	• Heating in cement kilns	–	Unknown
Chemicals	0.5	• Ammonia production • Heating and drying	Major	Existing (gray hydrogen)
Mining	2	• Tracks on fuel cells	–	Unknown
Power and heat	25.7	• Seasonal power storage • Residential and industrial heating	Minor	Long-term
Oil and gas	5.2	• Oil refining (Hydrotreating)	Minor	Existing (gray hydrogen)
Nonregulated GHG emissions	56.7	• Transport (FCEVs, hydrogen stations)	Major	Long-term

Note: * The share of regulated sectors in 2019 was calculated using the average of emission values from 2018 to 2020.

4. CONCLUSION

Decarbonizing the part of Kazakhstan's emission sectors with hydrogen is the priority for the longer term. Hydrogen should not bring another "Dutch disease" to the country's economy by becoming the only export material after the decades of hydrocarbon economy. But it should bring a competitive advantage to goods produced from various economic sectors of Kazakhstan by decreasing their carbon footprint. Achieving decarbonization in Kazakhstan with hydrogen requires more financial and time resources, as it involves the development of all elements in the chain of the hydrogen industry: production, storage and transportation, and utilization. The financial burdens of establishing a local hydrogen economy could be alleviated by firstly focusing on the export of low-carbon hydrogen in the near future. The focus should be later diverted towards the development of a local hydrogen utilization economy once the country starts to accumulate revenues and knowledge from hydrogen export.

While looking at policy aspects and the full technology chain of the hydrogen economy, we came to the following preliminary conclusions for Kazakhstan:

- Hydrogen is essential for achieving the carbon-neutrality goal of Kazakhstan. The role of hydrogen should be clearly defined in the long-term energy and decarbonization strategy of the country. The hydrogen strategy should provide confidence that there will be a marketplace for low-carbon hydrogen and relevant technologies **(Section 2.1)**.
- Foreign carbon regulation (especially the CBAM) may force Kazakhstan's exporters to adopt various decarbonization technologies, including hydrogen, to increase the competitiveness of products by lowering carbon intensity. The same effect can be expected from the ETS in Kazakhstan when it will get stronger in the future **(Section 2.2)**.
- Kazakhstan's unique location between the two largest hydrogen markets – the EU and the PRC – presents an opportunity to develop hydrogen export with a priority for low-carbon hydrogen (green/blue) to succeed even under strong carbon regulation **(Section 2.3)**.

- Our preliminary analysis indicated that blue hydrogen in Kazakhstan may have lower carbon intensity and lower cost than the global average, especially in the three largest hydrocarbon reservoirs of the country. Potential exists for green hydrogen production as well, but a high Capex is still expected. In both cases, the effects of hydrogen export on the water security of the country need to be considered **(Section 3.1)**.
- Hydrogen transport and storage infrastructure for exports should be developed in the near future. For a landlocked country like Kazakhstan, nearby hydrogen markets are available via pipeline and railways. Trucks could be considered for the transport of hydrogen within the country. The financial burdens of infrastructure development for hydrogen export could be shared between interested stakeholders (green and blue hydrogen developers, transit countries, and hydrogen importers) **(Section 3.2)**.
- Demand for hydrogen should be stimulated at a local scale to launch the hydrogen economy in Kazakhstan. Near-term utilization areas for low-carbon hydrogen in Kazakhstan should focus on existing industrial clusters (ammonia plants, refineries, and iron/steel factories). Long-term utilization areas are energy storage in the power sector, residential heating, and transportation **(Section 3.3)**.

There are three limitations to the deployment of hydrogen energy in Kazakhstan:

- R&D investment is needed to decrease technology costs and to build local capacity. Potential hydrogen research areas for Kazakhstan include hydrogen production from H_2S, water electrolysis technologies, storage and transportation of hydrogen in metal hydrides, fuel cells, and hydrogen-based fuel blends.
- Appropriate regulations should be approved at country level to establish clear rules for stakeholders. Regulations should cover both technical standards and investment policy. For first movers, mitigation measures for investment risks should be provided and unnecessary regulatory barriers should be eliminated.
- Further studies on the economic, environmental, and social impacts of the hydrogen value chain in Kazakhstan should be carried out.

REFERENCES

Abuov, Y., N. Seisenbayev, and W. Lee, 2020. CO_2 Storage Potential in Sedimentary Basins of Kazakhstan. *International Journal of Greenhouse Gas Control* 103: 103186. https://doi.org/10.1016/j.ijggc.2020.103186.

Andrew, R. M. 2021. The Global Carbon Project's Fossil CO_2 Emissions. https://doi.org/https://doi.org/10.5281/zenodo.5569235.

Annual Report of the NC "QazaqGaz". 2020. https://kase.kz/files/emitters/KZTG/kztgp_2020_rus.pdf (accessed 23 June 2022).

Aziz, M., T. Oda, and T. Kashiwagi, 2018. Comparison of Liquid Hydrogen, Methylcyclohexane and Ammonia on Energy Efficiency and Economy. 10th International Conference on Applied Energy, August, Hong Kong, China.

Bauer, C., K. Treyer, C. Antonini, C. et al. 2022. On the Climate Impacts of Blue Hydrogen Production. *Sustainable Energy & Fuels* 6: 66–75.

Bellosta von Colbe et al. 2019. Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives. *International Journal of Hydrogen Energy* 44(15): 7780–7808.

BP 2021. Full Report Statistical Review of World Energy 2021, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.

Bruce, S., M. Temminghoff, J. Hayward, E. Schmidt, EC. Munnings, and D. Palfreyman. 2018. Pathways to an Economically Sustainable Hydrogen Industry in Australia National Hydrogen Roadmap. CSIRO. Australia 18-00314_EN_NationalHydrogenRoadmap_WEB_180823.pdf (accessed 17 October 2022).

Cerniauskas S. 2020. Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study. *International Journal of Hydrogen Energy* 45: 12095–12107.

Chiyoda Corporation. SPERA Hydrogen System n.d. www.chiyodacorp.com/ (accessed 23 June 2022).

CoalAge. 2021. Hydrogen from Coal. https://www.coalage.com/features/hydrogen-from-coal/ (accessed 23 June 2022).

Dagdougui, H., R. Sacile, C. Bersani, A. Ouammi, A. 2018. *Hydrogen Infrastructure for Energy Applications Production, Storage, Distribution and Safety.* Elsevier.

Energy Connects. 2021. Svevind to build world's largest green hydrogen plan in Kazakhstan. https://www.energyconnects.com/news/renewables/2021/june/svevind-to-build-world-s-largest-green-hydrogen-plan-in-kazakhstan/ (accessed 17 October 2022).

EY. 2021. Tax Messenger. The Carbon Border Adjustment Mechanism. Ey-carbon-border-adjustment-mechanism-20-july-2021-tax-eng.pdf (accessed 17 October 2022).

———. 2022. Decarbonization in the Mining and Metallurgical Sector. (In Russian). Ey-metals-mining-decarbonization-v2-kfs.pdf (accessed 17 October 2022).

Forbes 2021. Kazakhstan in the Context of Climate Change. (In Russian)

Global Commercial Drive to Zero Program. 2022. Zero-Emission Technology Inventory n.d. https://globaldrivetozero.org/ (accessed 23 June 2022).

Hydrogen Council and McKinsey. 2021a. Hydrogen for Net-Zero. https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf (accessed 17 October 2022).

———. 2022. Decarbonization in the Mining and Metallurgical Sector. (In Russian). . 2021b. Hydrogen Insights. https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf (accessed 17 October 2022).

Hydrogen Council. 2021. Hydrogen Decarbonization Pathways. A Life-cycle Assessment. https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf (accessed 17 October 2022).

ICAP. 2021. Kazakhstan Emissions Trading Scheme. International Carbon Action Partnership 456:5.

IEA. 2017. World Energy Outlook. https://iea.blob.core.windows.net/assets/4a50d774-5e8c-457e-bcc9-513357f9b2fb/World_Energy_Outlook_2017.pdf (accessed 17 October 2022).

———. 2021. Global Hydrogen Review. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf (accessed 17 October 2022).

———. 2022. Decarbonization in the Mining and Metallurgical Sector. (In Russian). 2018. World Energy Outlook. https://iea.blob.core.windows.net/assets/77ecf96c-5f4b-4d0d-9d93-d81b938217cb/World_Energy_Outlook_2018.pdf (accessed 17 October 2022).

———. 2022. Decarbonization in the Mining and Metallurgical Sector. (In Russian). https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf (accessed 17 October 2022).

———. 2022. Decarbonization in the Mining and Metallurgical Sector. (In Russian). 2020. Cross-cutting: Hydrogen. 07-IEA-Cross-cutting.pdf (accessed 17 October 2022).

IEA Country Report. 2020. Kazakhstan Energy Profile. https://iea.blob.core.windows.net/assets/a398cfb3-4f0b-4b8f-b82e-47b8d7b93d52/KazakhstanEnergyProfile.pdf (accessed 17 October 2022).

International Policy, https://research.csiro.au/hyresource/policy/international/.

IRENA. 2022. Green Hydrogen Needs Industrial Policy Making and Certification. 11 March. https://irena.org/newsroom/articles/2022/Mar/Green-Hydrogen-Needs-Industrial-Policy-Making-and-Certification (accessed 28 June 2022).

Isidore, C. 2022. Why US Gas Prices Are at a Record, and Why They'll Stay High for a Long Time. *CNN Business.* 6 June. https://edition.cnn.com/2022/06/06/energy/record-gas-prices-causes/index.html (accessed 20 June 2022).

Jasyl Damu JSC. 2021. Greenhouse Gas Emission Trading System of the Republic of Kazakhstan. https://www.unescap.org/sites/default/d8files/event-documents/Aiman%20Yessekina_GFPN_Session%204_15Sept2021.pdf (accessed 1 July 2022).

Kazakhstan Government. 2012. Strategy 'Kazakhstan 2050' https://strategy2050.kz/en/page/multilanguage/ (accessed 17 October 2022).

———. 2013. The Green Economy Concept of Kazakhstan. https://greenkaz.org/images/for_news/pdf/npa/koncepciya-po-perehodu.pdf (accessed 6 July 2022).

———. 2021. National Allocation Plan 2021. https://primeminister.kz/ru/decisions/13012021-6 (accessed 1 July 2022).

KazEnergy. 2015. The National Energy Report 2015. https://www.kazenergy.com/upload/document/energy-report/NationalReport15_English.pdf (accessed 17 October 2022).

———. 2019. The National Energy Report 2019. https://www.kazenergy.com/upload/document/energy-report/NationalReport19_en.pdf (accessed 17 October 2022).

———. 2021. The National Energy Report 2021. https://www.kazenergy.com/upload/document/energy-report/NationalReport21_en.pdf (accessed 17 October 2022).

KMG Engineering. 2022. Competence Center for Hydrogen Energy Started Functioning in KMG Engineering. https://bit.ly/3AyOnJh (accessed 25 May 2022).

Ley, M. et al. 2014. Complex Hydrides for Hydrogen Storage – New Perspectives. *Materials Today* 17(3): 122–128. https://doi.org/10.1016/j.mattod.2014.02.013

LSM.KZ. 2021. Who in Kazakhstan Will Suffer from the Carbon Tax. https://lsm.kz/kakie-eksportery-kazahstana-postradayut-ot-uglerodnogo-naloga (accessed 20 June 2022).

Martemyanov, S. M., A. A. Bukharkin, B. T. Ermagambet, and Z. M. Kasenova. 2021. Field Test of In Situ Conversion of Coal. *International Journal of Coal Preparation and Utilization* 00: 1–11. https://doi.org/10.1080/19392699.2021.1957855.

Messerle, V., A. Ustimenko, and O. Lavrichshev. 2021. Plasma-fuel Systems for Clean Coal Technologies. *Proceedings of Institution of Civil Engineers: Energy* 174: 79–83. https://doi.org/10.1680/jener.19.00053.

Ministry of Energy. 2022. Information on the Construction of Large Renewable Energy Facilities for the 1st Quarter of 2022 https://www.gov.kz/memleket/entities/energo/documents/details/296510?lang=ru (accessed 23 June 2022).

Ministry of Industry and Infrastructural Development (MIID). 2022. Cargo Transportation through the Seaports of Aktau and Kuryk along the TMTM Route Increased by 41%. https://www.gov.kz/memleket/entities/miid/press/news/details/360035?directionId=2395&lang=ru (accessed 23 June 23 2022).

Ministry of Justice. 2017. On the Results of Calculating Greenhouse Gas Emission Quotas for 2018–2020. https://adilet.zan.kz/rus/docs/P1700000873 (accessed 20 June 2022).

Niaz, S., T. Manzoor, and A. Pandith. 2015. Hydrogen Storage: Materials, Methods and Perspectives. *Renewable and Sustainable Energy Reviews* 50: 457–469.

OECD 2017. Promoting Clean Urban Public Transport in Kazakhstan. https://www.oecd.org/environment/outreach/Kazakh%20Transport%20brochure%20WEB.pdf (accessed 17 October 2022).

Overview CAREC Program. 2021. Overview Study of Ports and Logistics in CAREC Countries. 59–75. https://www.carecprogram.org/uploads/Ports-and-Logistics-Scoping-Study-in-CAREC_web.pdf (accessed 17 October 2022).

Ren, J., N. M., Musyoka, H. W. Langmi, M. Mathe, and S. Liao. 2017. Current Research Trends and Perspectives on Materials-based Hydrogen Storage Solutions: A Critical Review. *International Journal of Hydrogen Energy* 42: 289–311.

Reuters. 2022. Kazakhstan to Cut Gas Exports by 2 bcm to Meet Domestic Needs. 9 June. https://www.reuters.com/article/kazakhstan-gas-idUSL1N2XW1KU (accessed 23 June 2022).

Robertson, H. 2022. Germany Takes 'Bitter' Decision to Fire up Coal Power Plants as Russia Chokes off its Vital Natural Gas Supplies. *Business Insider*. 20 June. https://www.businessinsider.com/germany-coal-power-plants-russia-cuts-natural-gas-climate-energy-2022-6 (accessed 6 July 2022).

Senate of the Parliament of the Republic of Kazakhstan. 2019. Water Security of Kazakhstan: State, Problems and Recommendations. https://senate.parlam.kz/ru-RU/analyticsinformationsenate (accessed 24 May 2022).

Sunny, N., Bernardi, A., Danaci, D., Bui, M., Gonzalez-Garay, A., Chachuat, B. 2022. A Pathway Towards Net-Zero Emissions in Oil Refineries. *Frontiers in Chemical Engineering* https://www.frontiersin.org/articles/10.3389/fceng.2022.804163/full.

Tokmurzin, D., B. Aiymbetov, B. Abylkhani, and A. Yagofarova, 2019. Fixed-Bed Gasification and Pyrolysis of Organic Fraction of MSW Blended with Coal Samples. *Chemical Engineering Transactions* 7: 163–168. https://doi.org/10.3303/CET1972028.

UN PAGE. 2021. Kazakhstan Unveils Doctrine for Carbon Neutrality by 2060. https://www.un-page.org/kazakhstan-unveils-doctrine-carbon-neutrality-2060 (accessed 6 July 2022).

Wu, X., H. Zhang, M. Yang, W. Jia, Y. Qiu and L. Lan. 2022. From the Perspective of New Technology of Blending Hydrogen into Natural Gas Pipelines Transmission: Mechanism, Experimental Study, and Suggestions for Further Work of Hydrogen Embrittlement in High-strength Pipeline Steels. *International Journal of Hydrogen Energy* 47(12): 8071–8090.

Zholdayakova, S., H-H. Uchida, M.R. Harada, Sato M., R. Gemma, Y. Matsumura, 2020. A Proposal for Water Transportation by a Hydrogen Energy System －A Feasibility Study for Kazakhstan, *Proceedings of the School of Engineering of Tokai Universit*y 45: 1–6. https://doi.org/10.18995/24343641.45.1.

Zuttel, A. 2003. Materials for Hydrogen Storage. *Materials Today* 6(9): 24–33.