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Hydrogen Storage Materials: Promising Materials for Kazakhstan’s Hydrogen Storage Industry

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Abstract

Hydrogen, widely recognized as an efficient and clean energy carrier, holds significant promise for transforming future energy systems. Despite advances in hydrogen production and cost reduction, challenges in hydrogen storage continue to impede its widespread adoption. Traditional storage methods, such as high-pressure tanks and liquid hydrogen, have limitations related to high energy and resource costs. Solid-state materials offer a safer and more reliable alternative for hydrogen storage under various operating conditions. This review article provides an in-depth analysis of hydrogen storage materials, focusing on metal hydrides, complex hydrides, and carbon-based materials, with particular attention to their thermodynamic, structural, and kinetic properties. Additionally, the article explores the potential application of certain materials in Kazakhstan's hydrogen market, highlighting the country's rich mineral resources and existing industrial infrastructure. By leveraging these resources, Kazakhstan can play a crucial role in advancing hydrogen storage technologies and contributing to global decarbonization efforts. The review aims to offer comprehensive insights into the current state and prospects of solid-state hydrogen storage materials, emphasizing their relevance and potential impact on Kazakhstan's energy sector.

1. Introduction

In 2023, the Intergovernmental Panel on Climate Change (IPCC) published its Sixth Assessment Report [1], highlighting the acute impact of global warming on regional increases in forest fires, abnormal heat waves, frequent heavy rainfall, droughts, and floods. It is noted that the cause of this is greenhouse gases (CO_2, CH_4, H_2O, N_2O, NO_2) emitted during the development of industry and innovations, which have led to an average planetary temperature rise of 1.1 °C. Additionally, over the past 200 years, humanity has been responsible for the release of 2.150–2.630 trillion tons of CO_2 into the atmosphere [1].

Amid growing concerns about climate change and the depletion of fossil fuels, the global community is actively seeking alternative energy sources. A review of the global transition to renewable energy sources was prepared by a group of authors from the Department of Energy Policy on Sustainability, Technology, and Forecasts [2]. According to this report, China leads in the transition to renewable energy sources, achieving an energy production level of 1.45×10^6 MW in 2023. In comparison, the European Union and the United States produced 6.40×10^5 and 3.85×10^5 MW of energy, respectively, while Kazakhstan produced 5660 MW using wind farms and solar panels (Fig. 1a). All the aforementioned countries consider hydrogen as a versatile, environmentally friendly energy carrier capable of playing a key role in the decarbonization of the global economy [3].

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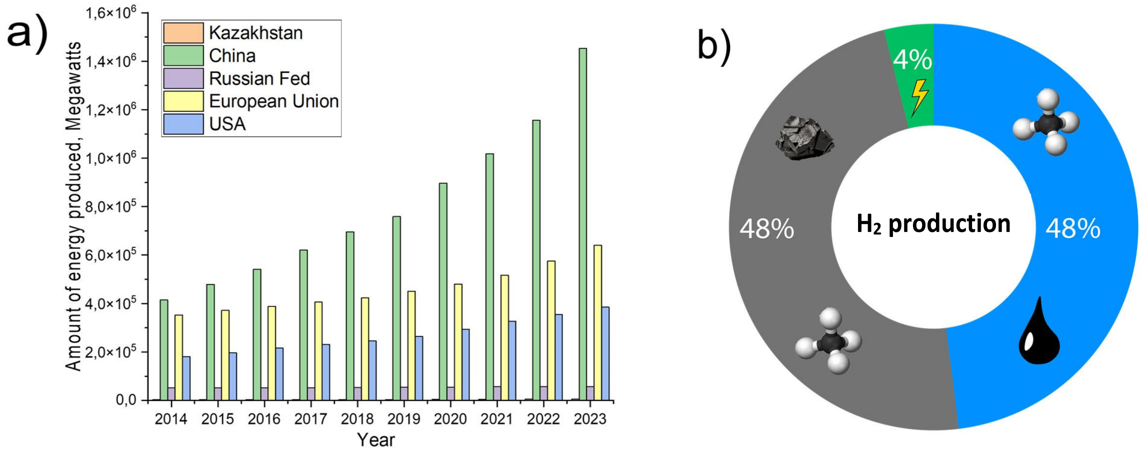

Fig. 1. A) Comparative characterization of the amount of energy produced by renewable energy sources in the period 2014-2023 [4]; B) Share of hydrogen production from different energy sources [2].

According to the International Energy Agency (IEA), global hydrogen production in 2022 amounted to 95 million tons, which is 3% more compared to the previous year [2]. Hydrogen accounts for 2% of the global energy market. Most of this hydrogen is produced from fossil fuels: 48% from natural gas and 30% from oil (gray hydrogen) and about 18% from coal (brown hydrogen). Only 4% of global hydrogen production in 2025 will be low-carbon hydrogen (green and blue hydrogen) (Fig. 1b). Green hydrogen is produced through an electrolysis process powered by renewable electricity, having no impact on the climate; blue hydrogen is grey hydrogen whose carbon dioxide emissions are captured and stored underground [2]. The share of investments in industrial hydrogen production is growing each year. According to the Hydrogen Council and McKinsey & Company (December 2023), over 1,400 hydrogen projects were announced in 2023, representing 7% of the final investment decision (FID), which corresponds to $570 billion in investments and 45 million metric tons per year of clean hydrogen. Despite increased funding for the development of hydrogen energy, "green" hydrogen, produced by water electrolysis using renewable energy, is considered the most promising. However, its high cost ($7–30 per kg) compared to "fossil" hydrogen (around $1–2.4 per kg) hinders widespread adoption (see comparison in Table 1) [3].

However, beyond the production process, efficient hydrogen storage continues to be a significant obstacle to its broad adoption in energy applications [4,5]. To date, several methods have been explored for storing hydrogen, including high-pressure compression, low-temperature liquefaction, high-pressure tanks, storage in solid-state (absorption) or porous materials (adsorption), and chemical carriers (NH_3, methanol, end some organic compounds) [6,7]. Physical storage (high-pressure compression, low-temperature liquefaction, high-pressure tanks) requires high pressure and low temperatures and special reservoirs (tanks, balloons and salt caverns etc.) for significant hydrogen uptake, which complicates its practical application [8]. Solid-state material-based storage is considered the safest and most practical solution to address the challenges associated with hydrogen transportation and storage. Potential materials for hydrogen storage through physisorption include carbon-based compounds such as graphene, carbon nanotubes, and carbon black (and many others), as well as metal oxides, metal-organic frameworks (MOFs), and covalent-organic frameworks (COFs) [9–11]. Alternatively, hydrogen can be

Table 1. Comparison of some characteristics of main hydrogen production methods.

Indicator	Water electrolysis	Coal gasification	Methane pyrolysis	Steam conversion
Production area, km^2	0.03	0.1	0.07	0.05
Energy consumption per 1 t of H_2, GJ/t	214.2	24.4	18.9	8.1
Presence of negative by-products	No	Yes	Yes	Yes
Presence of useful by-products	No	Yes	Yes	No
Cost per 1 kg of hydrogen, $	7.0–30.0	2.0–2.4	2.0–2.6	1.2–1.6

stored via chemisorption, where hydrogen atoms react with solids to form hydrides. This approach utilizes compounds such as metal/alloy hydrides and complex metal hydrides [11–13]. This current review is targeted to consider only metal/alloy hydride compounds due to their high safety, high hydrogen storage content, and perspective in new materials. Besides this, we can recommend recent reviews that have extensively covered specific hydrogen storage materials, including metal/alloy and complex hydrides [14–17], MXene compounds, carbon-based materials [18–20], metal-organic frameworks (MOFs) [21–23], covalent organic frameworks (COFs) [24–26] and zeolites [27–29]. In this review, we provide a comprehensive examination of the research on various solid-state hydrogen storage materials (especially targeting metal/alloy/complex hydrides) as well as the thermodynamic approach of selecting metal hydrides with consideration of evaluation criteria and methods for developing alloys for hydrogen storage. In addition, we will consider promising intermetallic compounds and arguments in favor of their industrial production in the conditions of Kazakhstan's infrastructure.

2. Hydrogen storage methods

To date, there are several methods (technologies) for hydrogen storage that are either directly applicable or in the final stages of development. These technologies can be divided into two main categories: hydrogen storage based on changing physical properties, by altering pressure and temperature (physical storage), and storage in materials. The main approaches among them include the following: storage of compressed gaseous hydrogen (increasing gas pressure); liquefaction and storage in special cryogenic containers (reducing temperature); cryo-compressed storage (a combination of compression and temperature reduction); solid-state storage using various storage materials [30,31]. Such of these methods has its own advantages and disadvantages (which will be discussed in more detail in the following chapters), necessitating further research and development in this area. A summary of the operating conditions and capabilities of the listed methods (temperature, pressure, capacity) is presented in Table 2 [32]. When comparing the two main hydrogen storage technologies (physical storage and material-based storage), it is evident that using combinations of temperature and pressure to change the physical state of the H_2 gas requires special containers and is less safe than using materials that can bond with hydrogen molecules or atoms, both physically and chemically, thereby increasing storage density and safety. However, most advanced material-based storage technologies are still in the stages of laboratory research and demonstration [31].

Table 2. Storage capacities and energy densities realized by different hydrogen storage technologies. Adapted from [32]

Hydrogen storage	H_2 storage materials	Grav. Capacity (Theor./Exper.) [weight %]	Volumetric energy density		Operating pressure [bar]	Operating temperature [K]	Ref.
			Theor./Exper. [kWh/dm^3]	[kg H_2/dm^3]			
H_2 at high pressure	-	100	0.8	9–18	350	Environment	[33]
	-	100	1.3	9–18	700	Environment	[33]
Liquid H_2	-	100	2.2	71	1-10	20	[33]
Cryo-Compressed hydrogen storage	-	100	1.6	0.07–0.08	150	35	[54]
Metal hydrides	MgH_2	7.6 (5.5)	3.67 (2.65)	0.110 (620 K, 5 bar)	-*	593	[34,35]
	TiFe	1.86 (1.5)	4.03 (3.25)	0.115 (300 K, 1.5 bar)	4.1	265	[36]
	$TiMn_2$	1.86 (1.15)	4.09 (2.53)	-	8.4	252	[36]
	$LaNi_5$	1.49 (1.28)	4.12 (3.53)	0.118 (300 K, 2 bar)	1.8	285	[36]
Complex hydrides	$LiBH_4$	18.5 (13.4)	4.08 (3.02)	0.120 (553 K)	-*	573	[37,38]
	$NaAlH_4$	7.5 (3.7)	3.20 (1.58)	0.093 (> 520 K)	-*	473	[37,38]

* - The equilibrium pressure at 298 K of these hydrides is well below values suitable for practical applications

2.1. Physical-based storage methods

Compression storage in balloons. Compressing hydrogen and storing it in high-pressure cylinders is the simplest and most mature method. There are 5 types of cylinders for storing hydrogen under high pressure. Type I includes steel and aluminum cylinders, weighing about 50–500 kg, which have been used since the late 19th century. These cylinders can withstand pressures up to 200–300 bar [39]. However, due to their low gravimetric density and large size, they can only be used for stationary applications. Type II cylinders are steel cylinders wrapped with carbon fiber to reinforce the cylindrical body of the metal cylinder. They are typically used for intermediate pressure storage, around 300 bar [40], and are used for stationary storage at hydrogen refueling stations [41]. Type III Cylinders have a fully wrapped composite material with a metal liner, often aluminum. They offer a significant weight reduction compared to Type I and II cylinders and are capable of storing hydrogen at pressures up to 700 bar. This makes them suitable for mobile applications, including vehicles and transportable storage solutions. Type IV Cylinders are the most advanced and lightweight, featuring a non-metallic liner (usually made of polymer) fully wrapped with a composite material such as carbon fiber. They can also handle pressures up to 700 bar. These cylinders are highly favored in automotive applications due to their weight efficiency and high performance [42,43].

Underground hydrogen storage. For medium- and long-term hydrogen storage in a huge quantity, salt caverns, aquifers, and depleted gas reservoirs are also used. Salt caverns are considered the best options not only due to the tightness and mechanical properties of salt but also because of the viscoelastic rocks that provide excellent sealing for gases [44]. However, the volumes of the caverns (comparing to other underground systems) are small, and they are not widely distributed [45]. Often, for storing large volumes of hydrogen, depleted gas reservoirs are used. These reservoirs have large capacities and well-known geological and chemical characteristics of the formations, but the purity of the hydrogen can be compromised by residual natural gas. The advantages of aquifers include large volumes and the presence of an impermeable layer (in some formations) to prevent the migration of stored hydrogen. However, due to the risk of potential leaks along unidentified faults caused by the porosity of the aquifer, as well as biochemical reactions and reactions of hydrogen with minerals in the reservoir rocks, aquifers have not found widespread application [46].

Liquid hydrogen storage. Liquid hydrogen (LH_2) has significantly higher gravimetric and volumetric density compared to compressed gaseous hydrogen. However, the liquefaction process of hydrogen is more complex and energy-intensive than its compression or the liquefaction of other common gases due to several reasons [47]:

a) very low boiling temperatures (20.28 K at 1 bar) and low critical point (33 K) that refers to the highest temperature and pressure at which hydrogen can exist as a liquid. Beyond this point, hydrogen cannot be liquefied by increasing pressure alone, regardless of the temperature.

b) The small size of hydrogen molecules makes it nearly an ideal gas at relatively high temperatures - its Joule-Thomson coefficient is positive only at temperatures below 202 K, which means that at temperatures above 202 K, hydrogen will heat up upon expansion, and at temperatures below 202 K, it will cool down, complicating the liquefaction process [48].

c) The enthalpy of vaporization of parahydrogen at 20 K (447 kJ/kg) is lower than the enthalpy of the exothermic conversion of normal hydrogen to equilibrium hydrogen at the same temperature (532 kJ/kg) due to the conversion from ortho- to parahydrogen. In other words, converting normal hydrogen to its equilibrium state at 20 K requires more heat (532 kJ/kg) compared to the amount of heat needed for its vaporization (447 kJ/kg). This additional heat contribution complicates and increases the energy costs of the hydrogen liquefaction process [48].

Modern hydrogen liquefaction plants use an advanced system combining the Linde-Hampson cycle with an expansion machine, which was invented in 1902 by Georges Claude. In Germany, for example, there is a hydrogen liquefaction plant in Leuna, which began operations in 2007 and has a production capacity of 5.5 metric tons per day (mTPD). The second plant in Leuna with a doubled capacity (10 mTPD) was recently launched in 2021 and employed Linde's advanced hydrogen liquefaction technology, which includes preliminary cooling with liquid nitrogen and multiple sets of low-temperature expansion turbines and heat exchangers with integrated ortho- to parahydrogen conversion catalysts. The plant in Ingolstadt with the capacity of 4.4 mTPD, which had been operating since 1992, was closed (in 2021) due to the utilization of older technology that was less energy-efficient compared to more recent facilities. All these facilities use Claude's technology with preliminary cooling by liquid nitrogen and are operated by Linde AG [25]. At this stage of development, the hydrogen liquefaction industry uses more sets of expansion turbines operating at low temperatures and more heat exchangers with integrated ortho- to parahydrogen conversion catalysts [49].

The main technological challenge in storing LH_2 is minimizing evaporation losses due to thermal leaks caused by the thermal conductivity of container materials, radiation, and the conversion of ortho- to parahydrogen. Typical evaporation losses range from 1% to 5% per day. Integrating a cooling system into a multilayer insulated tank can potentially eliminate these losses.

Cryo-Compressed hydrogen storage (CCH_2). In recent years, CCH_2 has been gaining increasing attention from researchers and industry as a promising method that combines the advantages of liquefaction and compression. This approach was developed to overcome the limitations of traditional hydrogen storage methods. Although liquid hydrogen provides high storage density (71.0 kg/m^3 at 20 K and 4 bar) compared to compressed gas (39.1 kg/m^3 at 300 K and 700 bar), evaporation losses limit its application, especially in vehicles [31]. In response to this issue, BMW initiated research on storing hydrogen at temperatures above 20 K and pressures below 700 bar [50].

According to the work conducted by Yanxing et al. [51], the key advantage of CCH_2 lies in achieving higher density than LH_2 at relatively higher temperatures. For example, at 35 K and 150 bar, the density of hydrogen exceeds that of its liquid state. Under these conditions, hydrogen is in a supercritical state or a two-phase region. There are two main approaches to obtaining CCH_2:

1) from gaseous hydrogen that requires multistage compression with intermediate cooling followed by cryogenic cooling. This method is technically complex and energy-intensive [51].

2) From liquid hydrogen that developed as part of a joint project by BMW AG and Linde AG. It uses a high-pressure cryopump and an evaporator to convert LH_2 into CCH_2. This process is significantly simpler and more efficient [50]. The second method is particularly promising for integration with hydrogen refueling stations based on LH_2, as it does not require intermediate storage when directly refueling fuel cell vehicles [52,53].

Thus, CCH_2 technology opens new opportunities for efficient hydrogen storage, especially in the transportation sector. However, further research is needed to optimize the process, reduce energy costs, and develop the necessary infrastructure [54].

2.2. Solid-state hydrogen storage materials

In the context of safe and environmentally friendly hydrogen storage technologies, solid-state storage methods attract particular attention. Solid-state hydrogen storage methods are divided into adsorption and absorption storage mechanism and compounds respectively as we see in Fig. 2 [55]. Absorption is a bulk phenomenon where hydrogen atoms chemically bond (are absorbed) into the metal lattice, forming a hydride (metal hydrides, complex hydrides etc.). Adsorption is a surface phenomenon where hydrogen atoms/molecules are held in the pores, on the surface, and in the cracks of adsorbing materials, i.e., physically bonded to the storage material (carbon nanotubes, metal-organic frameworks, etc.).

A key advantage of such systems is the ability to release hydrogen at moderate temperatures and pressures. Compared to commercialized technologies (compressed hydrogen, LH_2 and CCH_2), absorption/adsorption storage systems have several significant advantages:

- increased safety compared to gaseous or liquid storage, solid-state systems present a lower risk of leaks and explosions [56];

- high volumetric storage density than potentially exceeds other methods, which is particularly important for compact applications. For example, the volumetric hydrogen capacity for compressed H_2 at 350 bar and 700 bar is 23.3 and 39.0 g/l at 300 K, respectively [57]. Comparing liquid hydrogen storage (20 K, 4 bar) and cryogenic technologies (72 K, 500 bar), there are slight differences – 71.7 and 74.7 g/l, respectively [51,52]. Using solid hydrogen carriers, the volumetric capacity can reach up to 150 g/l [37]. Currently, values of 86 and 110 g/l have been achieved using MgH_2 [58,59];

- operational flexibility that allows to operate at normal temperatures (25–100 °C) and pressures (1–5 bar) simplifies storage design and reduces energy costs.

Due to current limitations, research in hydrogen storage is actively focused on finding and developing new materials with optimal hydrogen sorption and desorption characteristics, as well as safe operation. Among the most promising materials for commercialization are metal hydrides, complex hydrides, carbon-based adsorbent materials, and metal-organic frameworks (Table 3) [55].

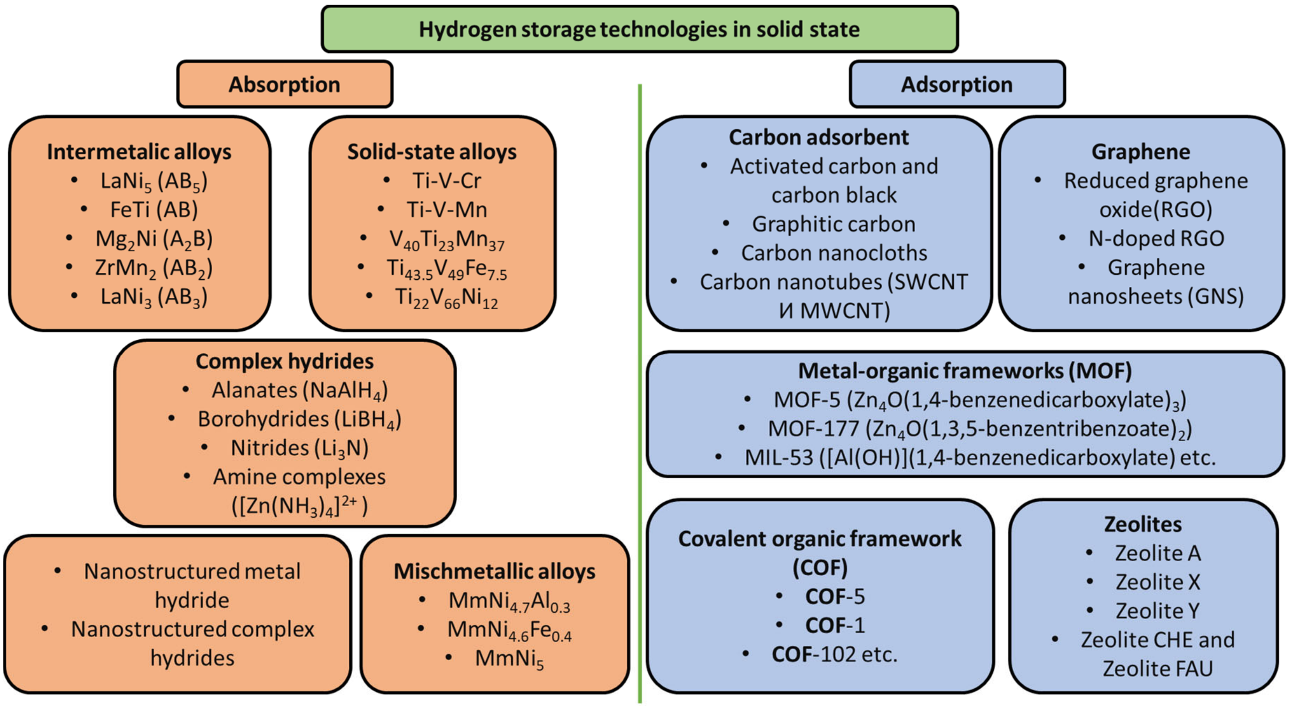

Fig. 2. Solid-state hydrogen storage systems.

Table 3. Comparison of most promising and commercialized materials for solid-state Hydrogen Storage.

Material	Gravimetric capacity (wt.%)	Advantages	Disadvantages	Economic Impact	Companies	Ref.
Light metal hydrides ($LiAlH_4$)	up to 10%	High energy density (around 10 Wh/g), stability (up to 500 cycles)	High cost, complex desorption (desorption temperature around 423 K)	High cost, requires scaling	ECD Ovonics	[60]
Transition metal hydrides ($LaNi_5H_6$)	1-2%	Fast sorption/desorption kinetics, low temperatures, low (around 298–373 K), low pressure	Low capacity, high cost, limited cycle life (around 100-200 cycles)	High cost, requires mass production	HBank Technologies	[61]
Aluminum hydrides ($NaAlH_4$)	up to 5.6%	High hydrogen density (around 5.6 Wh/g), low desorption temperature (around 373 K)	Toxicity, need for catalysts, limited cycle life (around 300-400 cycles)	Potentially cost-effective with mass use	Toyota, GM	[62], [63]
Carbon nanotubes	2-4%	High specific surface area, light weight, stability (up to 1000 cycles)	High production cost, complexity in scaling	Cost reduction with nanotechnology development	Nanoshel, Arkema	[64], [65],
Graphene materials	up to 7.7%	High specific surface area, high chemical stability (up to 1000 cycles)	High cost, complexity in production	Cost reduction with nanotechnology development	XG Sciences, Vorbeck Materials	[66], [67]
MOFs	up to 9%	Huge specific surface area, tunable porosity, stability (up to 500 cycles)	High synthesis cost, potential instability at high temperatures (above 473 K)	High cost, potentially cost-effective at industrial scale	BASF, MOF Technologies	[68]
Zeolites	1-3%	High thermal stability, availability, stability (up to 1000 cycles)	Low capacity, slow sorption/desorption kinetics	Available, but low capacity limits applications	Zeolyst International, Tosoh Corporation	[69]

In this review, we will pay more attention to metal/alloy/complex hydrides due to their faster potential in commercial application high gravimetric capacity and lower cost comparing to adsorption materials. For example, complex hydrides consisting of light elements such as sodium (Na) and lithium (Li) have attracted special attention as solid-state materials for hydrogen storage, as traditional metal hydrides primarily consist of heavy elements. Sodium alanate ($NaAlH_4$), due to its moderate operating temperature and pressure [70], favorable thermodynamics, and satisfactory gravimetric capacity, is a potential candidate for use in proton-exchange membrane (PEM) fuel cell systems and direct H_2 absorbent [71]. Despite having a gravimetric capacity of 7.5 wt.% it has sluggish kinetics, low reversibility at temperatures below 423 K and releases hydrogen in three stages according to the following reactions [72]:

$$NaAlH_4 \rightarrow Na_3AlH_6 + 2Al + 3H_2 \qquad T = 185\text{-}230\ °C,\ 3.7\ H_2\ wt.\% \qquad (1)$$

$$Na_3AlH_6 \rightarrow 3NaH + Al + 0.5H_2 \qquad T = 260\ °C,\ 1.9\ H_2\ wt.\% \qquad (2)$$

$$3NaH \rightarrow 3Na + 0.5H_2 \qquad T = 435\ °C,\ 1.9\ H_2\ wt.\% \qquad (3)$$

To reduce the desorption temperature of H_2 and improve the performance of $NaAlH_4$, it is alloyed with various catalysts such as metals, metal oxides, metal halides, and carbon materials [73]. Due to the high cost of $NaAlH_4$, a positive economic effect is achieved by scaling up production to reduce costs. The development and commercialization of alanate production technology for hydrogen storage have been carried out by ECD Ovonics since the 1960s [74]. Currently, the patents and technology for metal hydrides and hydrogen storage materials from ECD Ovonics have been acquired by BASF [60].

The most common materials for solid-state hydrogen storage are intermetallic compounds, which are metal alloys with the formula A_xB_y, categorized according to the crystal lattice structure (Table 4) [17].

AB_5-type compounds, such as $LaNi_5$, are characterized by a hexagonal structure and include rare earth elements and transition metals. These materials are known for their good cyclic stability and ease of activation (a preliminary process before the main hydrogenation/dehydrogenation that promotes greater H_2 accumulation/release). For example, $LaNi_5$ has a hydrogen capacity of 1.5 wt.% at room temperature and a pressure of 5 bar [75]. $TiMn_2$, $ZrMn_2$, and ZrV_2 alloys belong to the AB_2-type compounds, which also have a hexagonal structure and include elements such as Ti, Zr, Hf, Cr, V, Mn, and Fe. These materials demonstrate high capacity, excellent kinetics, and long lifespan. One of the good representatives of AB_2 family is $TiMn_{1.4}V_{0.62}$, which has a hydrogen capacity of 2.15 wt.%. Despite the activation challenges compared to AB_5, a high concentration of Zr or Mn in the AB_2 alloy composition can facilitate this process [76]. Cubic body-centered AB-type compounds have a low molar mass and a high gravimetric hydrogen capacity in the range of 1.7–1.9 wt.% (e.g., FeTi). However, the presence of a surface oxide film requires high temperatures for activation [77,78]. Despite the small numbers of AB_3 compounds (e.g., $ErFe_3$, Zr_3Rh, $La_{1.8}Ti_{0.2}MgNi_{8.7}Al_{0.3}$, $(Ni,Al)_{3.5}$), they are characterized by a unique structure due to the simultaneous presence of AB_5 and AB_2 structures within the crystal lattice. These compounds are being intensively studied to achieve optimal hydrogen capacity and kinetics [79]. Solid solutions involve the substitution of elements within the intermetallic compound lattice, allowing for property modification. For example, Mg_2Ni, a typical representative of A_2B solid solutions, has a hydrogen capacity of 3.8 wt.% but is characterized by a high

Table 4. Classification of intermetallic compounds for solid-state hydrogen storage

Intermetallic compound	Alloy example	Capacity (H/M)	Capacity (wt.%)	Alloy structure
AB_5	$LaNi_5$, $MmNi_5$	1.00	0.80–1.40	Haucke phase, hexagonal
AB_2	$TiMn_2$, $ZrMn_2$, ZrV_2	1.30	1.50–2.15	Laves phase, hexagonal or cubic
AB	TiFe	1.86	1.70–1.90	Cubic, CsCl-type or orthorhombic, CrB-type
AB_3/A_2B_7	$CeNi_3$	2.14	1.80	Hexagonal, $NbBe_3$-type
Solid solutions	V, Ti-V, Mg-Ni	2.00	3.00–7.60	Body-centered cubic

activation temperature. Replacing nickel with zinc in this compound reduces the activation energy and improves hydrogen absorption kinetics [80–82].

Carbon-based materials attract attention as promising adsorbents for hydrogen storage due to their unique physical and chemical properties [18]. Activated carbons are characterized by a specific surface area in general ranging from 500 to 2000 m²/g and a microporous structure. It has been shown that increasing the specific surface area (S_m) increases hydrogen capacity [83]. For example, in [84], superactivated carbon KUA5 (S_m = 3000 m²/g) was studied, and its hydrogen capacity at 298 K was found to be 16.7 g H_2/l (3.2 wt.%) and 37.2 g H_2/l (6.8 wt.%) at 20 MPa and 50 MPa, respectively. Single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) are promising materials for hydrogen storage [85,86]. SWCNTs have a hydrogen storage capacity of 1.7 wt.% at 298 K and 120 bar. The specific surface area of these materials, with their developed microporous and mesoporous structure, ranges from 100 to 400 m²/g [87]. In a study on acid-treated SWCNTs [88], it was shown that at 77 K and 1 bar pressure, carbon nanotubes can adsorb 0.8 wt.%, and at 303 K and 31 bar pressures, they can adsorb 0.26 wt.% H_2. This indicates the potential for future research aimed at improving the sorption properties of carbon nanotubes through acid or alkaline surface treatment. Due to this, the study in article [89] focuses on the chemical modification of the surface MWCNTs, which have a developed S_m ranging from 400 to 1000 m²/g and a microporous structure, by incorporating SnO_2 into the structure. The pore size, morphology, and interaction between MWCNT and SnO_2 were significantly influenced by thermal treatment, resulting in high hydrogen storage capacities of 2.13 and 2.62 wt.% with hydrogenation times of 15 and 30 min, respectively.

Current research in carbon materials for H_2 storage focuses particularly on three key structures: graphene, fullerenes, and carbon aerogels (Table 5). Each of these structures has unique characteristics that determine their potential in hydrogen storage. Notably, graphene demonstrates impressive hydrogen storage capacity. Specifically, at temperatures of 296–298 K and a pressure of 60 bar, graphene can hold between 6.70 and 8.67 wt.% H_2 [90]. It is important to emphasize that the specific surface area of graphene varies widely from 250 to 2000 m^2/g. Moreover, the structure of graphene is characterized by the presence of micropores, mesopores, and macropores, which undoubtedly contribute to its high adsorption capacity [77]. Furthermore, considering fullerenes (C_{60}), it is necessary to note their somewhat lower but still significant hydrogen storage capacity. Specifically, at a temperature of 623 K and a pressure of 100 bar, fullerenes can hold up to 5 wt.% H_2 [91]. It should be emphasized that the specific surface area of fullerenes is slightly lower than other carbon compounds, ranging from 200 to 500 m^2/g, and their structure is predominantly microporous. However, it is important to consider that the activation energy for hydrogen in fullerenes is 83.1 kcal/mol, which unfortunately reduces their efficiency for hydrogen storage at low temperatures [92]. Finally, carbon aerogels deserve special attention. Notably, at a temperature of 77 K and a pressure of 30 bar, these materials can store up to 4.8 wt.% H_2. It is important to note that the specific surface area of carbon aerogels varies widely from 250 to 3110 m^2/g. Furthermore, the structure of these materials is characterized by the presence of micropores, mesopores, and macropores. It is particularly worth emphasizing that the large pore volume and continuous porosity make carbon aerogels exceptionally efficient for hydrogen adsorption [93].

Recently, materials such as metal-organic frameworks (MOFs) have gained popularity. These materials represent a class of compounds consisting of metal ions or clusters connected by organic ligands, forming a porous structure [90]. These materials possess a high specific surface area and pore vol-

Table 5. Potential carbon-based materials for hydrogen storage

Name of carbon material	Material structure	Average H_2 capacity (wt.%)	Hydrogen storage conditions	Ref.
Activated carbons	Porous structure	7	Room temperature, 500 bar	[84,94,95]
Carbon nanotubes	Porous structure	2.62	673 K, 50 bar	[87,88,96,97]
Graphene	Two-dimensional structure	8.67	Room temperature, 60 bar	[77]
Fullerenes	Spherical structure	5	Room temperature, 100 bar	[87,92,98]
Carbon aerogels	Highly porous structure	4.8	77 K, 30 bar	[93,99]

ume, making them promising for hydrogen storage [100]. In case of hydrogen storage application MOFs can be classified by their mechanism of interaction with hydrogen. The first mechanism is physical adsorption, where hydrogen adsorption on the surface and in the pores of MOFs occurs due to weak Van der Waals forces. Since hydrogen is molecular, it interacts with the surface of MOFs through electrostatic interaction forces. Hydrogen adsorption on MOFs is optimal at low temperatures (around 77 K) and high pressure, which allows for high hydrogen storage capacity. Examples of such materials include MOF-5, MOF-177, IRMOF-20 [101]. The chemisorption mechanism of hydrogen storage involves the formation of chemical bonds between hydrogen and active centers of MOFs, such as open metal sites. Notable representatives of chemisorption MOFs are Ni-MOF-74, Co-MOF-74 [102].

Let's consider several representatives of this class of materials in the context of hydrogen storage. First of all, it is worth noting MOF-5, which was one of the first thoroughly studied MOFs in the context of hydrogen storage. Notably, this material can hold up to 7.8 wt.% hydrogen under conditions of 77 K and 100 bar [103]. Next, IRMOF-20 deserves attention, demonstrating an even higher storage capacity – up to 9.1 wt.% hydrogen under the same conditions [104]. However, the most impressive results are shown by more modern developments. In particular, NU-100 has an exceptional hydrogen storage capacity, reaching 16.4 wt.% at 77 K and 70 bar [105]. Equally notable is NU-1501-Al, which can hold up to 14.5 wt.% hydrogen at 77 K and 100 bar [106]. Finally, special attention should be given to MOF-210, which currently demonstrates one of the highest recorded hydrogen storage capacities among all known materials. In particular, this MOF can retain up to 17.6 wt.% hydrogen at 77 K and 80 bar. However, when moving to room temperature (298 K), the mass% of hydrogen decreases to 1 wt.% at 20 bar [103]. Metal-organic frameworks (MOFs) hold significant potential for hydrogen storage, but their use faces several challenges. Some MOFs degrade or lose their properties when exposed to water or high temperatures, limiting their stability and durability. Although MOF-5 exhibits good hydrogen adsorption at cryogenic temperatures (< 120 K), its efficiency decreases significantly at room temperature. The production of MOFs requires complex and costly chemical processes, hindering mass production and commercial use. Additionally, the slow adsorption and desorption kinetics in some MOFs make them less suitable for applications requiring rapid response, such as hydrogen fuel cells. Achieving high hydrogen storage capacity often necessitates low temperatures and high pressures, complicating operation and increasing energy costs. These issues highlight the need for further research to develop more stable, efficient, and economically viable MOFs for hydrogen storage [107].

From the investigation to commercialization of technologies and materials for H_2 storage. There are several potential materials for hydrogen storage today, which is why the development and implementation of new hydrogen storage materials on a large scale is a key direction for many companies worldwide. BASF is one of the largest chemical companies in the world, actively engaged in research and development of new hydrogen storage materials, including metal hydrides and composite materials based on metal-organic frameworks and nanomaterials [60]. A leader in the supply and production of gases for industry and healthcare is Air Liquide. The company's active developments are focused on hydrogen storage systems based on compressed gas, liquid hydrogen, and adsorbent materials [108]. Recently, liquid organic hydrogen carriers (LOHC) have been gaining popularity, with German company Hydrogenious LOHC Technologies leading in their production. This technology allows for the safe storage and transportation of hydrogen at room temperature and normal pressure [109]. Carbon nanotubes and graphene materials are potential adsorbent materials for hydrogen storage. Nanoshel is engaged in the development and production of nanomaterials, including carbon nanotubes and graphene, which can be used for hydrogen adsorption and storage [110]. Founded in 1997, the American company Plug Power manufactures and develops hydrogen fuel cells and related infrastructure solutions. The company produces metal hydrides and composite materials for safe and efficient solid-phase hydrogen storage, which are used in high-pressure hydrogen storage cylinders. Fuel cell technologies, metal hydride systems, and hydrogen refueling stations are actively used in transportation and stationary hydrogen storage systems nowadays [111].

3. Current situation and perspectives of hydrogen economy in Kazakhstan

Nowadays, the hydrogen industry in Kazakhstan is in its infancy. Nevertheless, Kazakhstan is making significant strides in the field of hydrogen technologies and production. In January 2023, President Kassym-Jomart Tokayev of Kazakhstan described green hydrogen as a "promising direction" [112].

He announced that international experts believe Kazakhstan has the potential to become one of the top ten exporters in hydrogen energy. He also announced a $50 billion deal for green hydrogen production with the SVEVIND Group, which is currently one of the largest projects of its kind in the world [113]. This project aims to produce up to 2 million tons of green hydrogen annually by 2032, utilizing wind and solar energy to power electrolysis processes. This project is expected to create thousands of jobs and support both domestic use and export to Europe [114].

The government of Kazakhstan is actively supporting the development of hydrogen technologies through regulatory frameworks and incentives. These initiatives include research and development grants, tax breaks, and strategic roadmaps to integrate hydrogen into various industrial sectors such as chemical production, steel manufacturing, and transportation. For example, science 2020 there were several projects in «program-targeted funding» and «grant funding» financed by the Ministry of Education and Science of the Republic of Kazakhstan. Also, the Ministry of Energy has developed the Concept for the Development of Hydrogen Energy in the Republic of Kazakhstan until 2040 [115], the investment of which will amount to about 10 bln $. There are the main goals of this concept:

1) The primary goal is to decarbonize the energy sector and diversify energy sources, reducing reliance on fossil fuels. This aligns with global climate goals and sustainability commitments.

2) Implementation of pilot projects for hydrogen vehicles, including buses, trucks, and rail transport, particularly in large cities to minimize environmental impact. These projects will test the feasibility and safety of hydrogen technologies in transportation and housing sectors.

3) Development of infrastructure for hydrogen transport, filling stations, and experimental sites for hydrogen production and storage. This includes creating hydrogen clusters and enhancing the capacity for hydrogen production and distribution.

As was mentioned, the concept is perfectly aligned with the Strategy for Achieving Carbon Neutrality in Kazakhstan by 2060 [116]. The strategy includes plans to reduce the share of coal in electricity generation significantly. By 2030, the share of coal in the energy mix is expected to decrease from the current 68.9% to 40.1%. This reduction will be achieved through the natural decommissioning of coal-fired power plants and the promotion of alternative energy sources, thereby increasing the share of renewable energy in the total electricity production to 6% by 2025; 10% by 2030; and 45–50% by 2050 [117]. In the context of the global transition to renewable energy sources, Kazakhstan is demonstrating significant progress in investments in the energy sector. In the 2023, the volume of investments in the fixed capital of the country's energy sector reached 451.4 billion tenge, which is 47.5% higher for the same period of the previous year [118]. An analysis of the investment structure (for 2023) reveals key trends in the development of Kazakhstan's energy sector [118].

Traditional Energy: About 29% of investments are directed towards electricity generation by thermal power plants, indicating a continued dependence on fossil fuels, primarily coal and gas.

Renewable Energy Sources (RES):

- Wind Energy: Leads the RES segment with investments amounting to 175.8 billion tenge.
- Hydropower: Attracted 12.4 billion tenge in investments.
- Solar Energy: Received 39.1 million tenge.

Nuclear Energy: Investments in nuclear power plants amounted to 288.6 million tenge, indicating

Table 6. Major deposits of rare earth, noble, and heavy metals in Kazakhstan

Metal	Deposit Name	Subsoil User	Reserves	Ref.
Rare Earth Metals	Shokash (Shokash-Kendyrli),	JSC "Kazatomprom"	50 000 tons	[122]
	Kundybay	JSC "Kundybai Mining"	25 000 tons	[123]
Gold	Vasilyevskoye	JSC "Altyntau Resources"	360 tons	[124]
Copper	Bozshakol	JSC "KAZ Minerals"	1.2 million tons	[125]
Lead	Shalkiya	JSC "ShalkiyaZinc LTD"	5 million tons	[126]
Zinc	Ridder-Sokolnoye	LLP "Kazzinc"	6.5 million tons	[127]
Chromium	Kempirsai	JSC "TNC Kazchrome"	1.4 billion tons	[128]
Nickel	Verninskoye	"Eurasian Resources Group"	3 million tons	[129]
Cobalt	Aktogay	JSC "KAZ Minerals"	55 000 tons	[130]

a growing interest in this type of energy as a potentially "clean" source.

The distribution of investments (for 2023) reflects Kazakhstan's strategy to reduce dependence on hydrocarbons and coal, as well as its commitment to implementing technologies that contribute to reducing CO_2 emissions. Special attention should be given to the significant investments in wind energy (almost 39% from total investments), which may be due to the country's geographical and climatic features.

In the context of developing alternative energy sources, it is important to note the potential role of green hydrogen as a key component of Kazakhstan's future energy system. Since hydrogen is an energy carrier (fuel) and its storage in solid-state materials, primarily composed of metals and their compounds, is a promising direction, there is a strong dependence on the comprehensive processing of mineral raw materials and deposits of rare earth, noble, and heavy metals [119]. Kazakhstan's rich reserves of mineral ores allow the country to occupy leading positions in the global market for the extraction and processing of rare earth [120], noble, and heavy metals [119]. These resources provide a foundation for the development of the mining and metallurgical industries, which is a crucial step towards the production of intermetallic compounds [121]. The Table 6 below lists major deposits of rare earth, noble, and heavy metals in Kazakhstan.

The comprehensive processing of mineral raw materials in Kazakhstan is an important step in enhancing the country's economic potential. The implementation of modern processing technologies allows for increased added value of products, the creation of new jobs, and the stimulation of economic growth. Comprehensive processing also plays a crucial role in the production of intermetallic alloys, which are necessary for effective hydrogen storage. This, in turn, contributes to the development of hydrogen energy, which is a priority for Kazakhstan as part of its strategy to reduce carbon emissions and transition to sustainable energy sources [131].

4. Promising intermetallic alloys for hydrogen storage in Kazakhstan

In the context of the global transition to clean energy sources, Kazakhstan is actively seeking innovative solutions to develop its energy system. One of the key directions is the use of hydrogen technologies, which allow for efficient energy storage and utilization. For the successful implementation of hydrogen energy, the creation of reliable and efficient hydrogen storage systems is critically important. Intermetallic alloys represent a promising class of materials for these purposes due to their high specific capacity and stability.

Special attention is given to how hydrogen production stimulates the demand for materials used in its storage. This opens new horizons for the Kazakhstan industry, creating a production chain from the extraction of rare earth metals to the synthesis of advanced intermetallic compounds. In this section, we will explore which intermetallic alloys are most promising for use in Kazakhstan's conditions and how their application, considering the specifics of the country's mineral resource base and climatic conditions, can contribute to the development of the hydrogen economy.

4.1. Magnesium-based alloys (MgH_2)

In recent decades, magnesium alloys have proven to be a promising medium for hydrogen storage due to their lightweight structure, wide availability, and high reversibility. Magnesium can store about 7.7 wt.% hydrogen (110 kg H_2/m^3), which exceeds the storage density of compressed hydrogen (23 kg H_2/m^3 at 350 bar and 38 kg H_2/m^3 at 700 bar), as well as that of liquid hydrogen (71 kg H_2/m^3) [132,133]. Nevertheless, achieving of this high capacity and good cycling stability (sorption/desorption) is almost impossible due to surface oxidation processes and low kinetics.

Existing methods for synthesizing MgH_2, such as mechanical synthesis [134], thin-film technology [135], chemical hydrogenation through vapor deposition, melting, plastic deformation, chemical reduction, or electrochemical deposition [136], are expensive and energy-intensive. They also do not solve the key problem of surface oxidation when exposed to air, which significantly reduces the hydrogenation rate due to the formation of oxides. For this reason, surface activation methods for Mg (at 673–723 K in an H_2 environment) or alloying with various metals (Zr, Mn, Ti, V) that have a significant affinity for hydrogen and reversible H_2 sorption/desorption properties are applied. A notable example is the Mg_2NiH_4 alloy, which has a low hydrogen desorption enthalpy (ΔH = 64.5 kJ mol^{-1} H_2). Initially obtained in an induction furnace under argon, the Mg_2Ni alloy showed a hydrogen capacity of 3.6 wt.% at 573 K and 2 bar [137]. However, the high desorption temperature and low mechanical stability of the alloy force researchers to alloy with metals such as copper (Cu), zinc (Zn), palladium (Pd), chromium (Cr), manganese (Mn), cobalt (Co), zirconium (Zr), vanadium (V), rare earth elements (REE), and others up to 15 wt.% [132]. The resulting three-component Mg-based alloys showed improved kinetic and thermodynamic properties in the H_2 sorption/desorption cycle and during storage. Studies on alloying Mg_2Ni with these metals noted that the grain size of the metals and nickel during synthesis by spinning and melt crystallization affects the hydrogen capacity [138–140]. For example, in [141], the maximum hydrogen capacity of amorphous or nanocrystalline Mg-Ni-REE alloys is less than 5 wt.%, explained by the high content of Ni and REE with grain sizes of 100–150 nm. Following this work, further research focused on reducing the grain size of the initial precursors and optimizing the controlled synthesis of Mg_2Ni-Me alloys. Thus, nanocomposites based on magnesium, carbon catalysts [133], alloys with yttrium, cesium [142], and indium [143] were introduced into the Mg_2Ni system. Such alloying increased the hydrogen storage capacity to 6 wt.% and significantly reduced hydrogen desorption enthalpy (ΔH = 35–40 kJ mol^{-1} H_2).

In addition Mg_2NiH_4 and its modifications, promising magnesium-based alloys include Mg_2FeH_6 (5.5 wt.%) [144] and Mg_2CoH_4 (4.5 wt.%) [145]. These alloys can also be supplemented with various metals to reduce the dissociation enthalpy and prevent disproportionation reactions [146].

In Kazakhstan, the production of magnesium alloys for hydrogen storage can be aligned with the Ust-Kamenogorsk Titanium and Magnesium Plant (UKTMP) [147], which is a flagship of Kazakhstan's non-ferrous metallurgy and has significant capabilities for magnesium processing and production. Based on this plant, the production of magnesium-based alloys such as MgH_2, Mg_2Ni, Mg_2Fe, Mg_2Co, and Mg_2Ni-Me (Me = Cu, REE, Zn, Cr, Mn, Co, In, Al) can be implemented using the following synthesis methods: alloying and mechanical alloying, spinning, and melt crystallization.

4.2. TiFe based alloy and its derivatives

In the field of hydrogen storage materials research, AB-type intermetallic hydrides, particularly equiatomic TiFe alloys, stand out for their suitable characteristics. These alloys attract scientists' attention due to their high volumetric hydrogen capacity (1.9 wt.% H_2) [13,148], optimal thermodynamic parameters for absorption and desorption processes at low temperatures, and excellent cyclic stability [149,150]. The unique crystalline structure of TiFe, formed by the synergistic interaction of titanium and iron, creates ideal conditions for the reversible incorporation of hydrogen atoms [149].

The process of hydride formation in the TiFe alloy is a complex physical-chemical phenomenon. Upon interaction with gaseous hydrogen, dissociative chemisorption of H atoms occurs in the interstitial sites of the intermetallic crystal lattice. The hydrogenation of the TiFe alloy proceeds through three successive stages: formation of the solid solution $TiFeH_{0.1}$ (α-phase), transition to the intermediate hydride $TiFeH_{1.04}$ (β-phase), and finally, the formation of the saturated hydride $TiFeH_{1.95}$ (γ-phase). $TiFeH_{1.04}$ and $TiFeH_{1.95}$ are gray metal-like solids that outwardly resemble the original TiFe alloy. These hydride phases are very brittle and easily disintegrate upon exposure to air. The hydrogenation reaction is exothermic, while the desorption of H_2 is endothermic, indicating additional safety measures: in the event of accidental container depressurization, the endothermic reaction will cool the system, slowing down the release of hydrogen and preventing the rupture of the hydrogen storage container.

Modern methods for obtaining TiFe alloy at room temperature include Arc Melting [151], Direct Electrochemical Reduction [152], Solid-Oxide-Oxygen-Ion-Conducting Membrane (SOM) method [153], Mechanical Alloying [154], Self-Ignition Combustion Synthesis [155,156], and others. A recent review [157] covers activation and alloying methods with metals such as Co, Mn, Cr, Ni, Al, and Be, with additions in atomic weight of 0.1–0.2% Me. For example, in study [158], a quasi linear correlation was found between the energy/enthalpy of monohydride formation of the $TiFe_{1-x}M_x$ alloy and the hydrogen desorption plateau pressure using Density Functional Theory (DFT) modeling. In the series of three-component alloys $TiFe_{1-x}M_x$: TiFe > $TiFe_{0.9}Mn_{0.1}$ > $TiFe_{0.95}Cr_{0.05}$ > $TiFe_{0.9}Co_{0.1}$ > $TiFe_{0.9}Al_{0.1}$ > $TiFe_{0.9}Ni_{0.1}$ > $TiFe_{0.9}Cu_{0.1}$ a decrease in the hydrogen desorption plateau pressure from 10 bar to 1 bar was observed, indicating an improvement in the desorption properties of TiFe which is especially important in the transition to industrial scale.

In the context of Kazakhstan, considering the advantages and disadvantages of the methods for obtaining and activating TiFe and its derivatives, the following technologies are proposed as promising: a) Arc melting is melting metals using the heat from an electric arc at high temperatures in a controlled inert atmosphere, followed by prolonged homogenization to obtain TiFe and $TiFe_{1-x}M_x$ granules. This technology can be implemented at Transnational Company KazChrome (TNC Kazchrome), one of the

Table 7. Effects of alloying by different elements on $LaNi_5$ characteristics

Alloying element	Synthesis conditions	Improved properties	Deteriorated properties	Ref.
Mn	Ball milling, vacuum melting	Improved thermodynamic stability, faster hydrogen sorption kinetics	Reduced overall hydrogen storage density	[172]
Al	Introduction into $LaNi_{4.25}Al_{0.75}$ alloy, melting	Improved cyclic stability, faster hydrogen absorption kinetics	Reduced hydrogen storage capacity	[175]
Co	Substitution of Ni with Co, melting	Increased corrosion resistance	Slightly reduced hydrogen storage capacity	[174]
Fe	Ball milling, vacuum melting	Increased hydrogen storage capacity	-	[173]
Mg	Ball milling	Increased hydrogen storage capacity, fast absorption kinetics	-	[169, 176]
Sn	Substitution of Ni with Sn, melting	Fast absorption kinetics	Slight changes in hydrogen storage capacity	[171]
Cu	Substitution of Ni with Cu, melting	Improved charge and discharge times, reduced dissociation pressure	Slightly reduced hydrogen storage capacity	[170]
Ga	Substitution of Ni with Ga, melting	Increased thermodynamic stability	Reduced hydrogen storage capacity	[176]
Rh, Ir, Pt or Au	Substitution of Ni, melting	Increased plateau pressure	-	[75]

world's largest producers of chrome and ferroalloys [159]. Currently, the Aktobe [160] and Aksu [161] ferroalloy plants use direct current induction furnaces and 28 electric furnaces to produce high-carbon ferrochrome, ferrosilicochrome, ferrosilicomanganese, and ferrosilicon, producing more than 740 thousand tons of ferroalloys per year. This provides favorable opportunities for the introduction of TiFe alloy production. B) Mechanical Alloying is a suitable synthesis of nanocrystalline TiFe and $TiFe_{1-x}M_x$ through mechanical alloying in a high-energy ball mill. The same TNC Kazchrome has a crushing and screening complex used to obtain fractions of the main product ranging from 3 microns to nanometers [162]. The purpose of this crushing and screening complex is to produce convenient commercial products for further use by metallurgical complexes in the country and industrial enterprises with special needs. Minor re-equipment or appropriate modification of this complex can be suitable for large production of TiFe alloys. Therefore, to improve the efficiency of the process, it is necessary to optimize the production of nanostructured TiFe-type alloys and their alloying within the existing ferroalloy productions.

Thus, on the basis of the TNC Kazchrome complex, an enterprise or division for the production of intermetallic alloys based on TiFe and its derivatives can be established to increase the added value of Kazakhstan products.

4.3. Intermetallic alloys based on AB_5 compounds

Intermetallic hydrides based on AB_5 are widely researched materials known for their excellent properties and ability to operate at room temperature. AB_5-based hydrides are brittle and can be easily ground into [163], making them suitable for use in hydride containers [77]. $LaNi_5$ is the most famous representatives of these family, offering a hydrogen storage capacity of about 1.4 wt.% [14]. Unlike other solid-state hydrogen storage materials, $LaNi_5$ is commercially available and there are many existing patents ready to go for commercial implementation [164]. $LaNi_5$ is easily synthesized by ball milling Ni and La (1–10 μm after 5 h) [165,172–174]; induction, arc, or electron beam melting in vacuum or argon atmosphere of lanthanum and nickel metals (20–200 μm) [166]; electro-reduction method in molten

$CaCl_2$ (10–20 µm); reduction-diffusion process (300–500 nm) [167]. Based on the methods of obtaining $LaNi_5$, it can be concluded that there are limitations in particle size and a wide range (from 500 nm to 200 µm) of obtained particles.

An equally important measure in the operation of $LaNi_5$ and its derivatives is the activation process to improve kinetic and thermodynamic limitations. Although the activation of $LaNi_5$ is quick and simple, requiring only one hydrogen absorption/desorption cycle at relatively low temperatures (<373 K) and pressures (<100 bar), research on alloying with other metals continues to gain relevance. The Table 7 provides comparative characteristics of modified $LaNi_5$-based alloys, with quantitative characteristics available in the corresponding works. Many researchers have begun modifying the $LaNi_5$ alloy by replacing either La in the A positions, Ni in the B positions, or both. La can be replaced by other rare earth metals such as Ce, Pr, Nd, or even a mixture of these metals (so-called mischmetals [Mm]), forming a solid solution, as well as Zr and Mg [77,168]. The initial goal of replacing La to Mm was solely to reduce the cost of metal hydride compounds. Unexpectedly, the use of Mm led to improved crucial characteristics. Partial substitution of Ni with a combination of metals such as Mn, Fe, Co, Ni, Cu, and Al significantly improved the alloy's properties for hydrogen storage and battery applications, such as lower plateau pressure, better high-rate discharge, performance at low temperatures, and cycle stability of sorption/desorption (charge/discharge) [14,75,168–176]. Despite the costly and energy-intensive technology for producing AB_5-type alloy components, Kazakhstan has all the prerequisites for establishing large-scale production for the hydrogen energy industry.

As is well known, the main components of AB_5 alloys are rare earth metals (La, Ce, Pr, Nd, and their mixture in the form of Mm), nickel, cobalt, and aluminum. In accordance with the needs for these metals, the following arguments are presented in favor of industrial production of alloys such as $LaNi_5$, $LaNi_{4.25}Al_{0.75}$, $MmNi_5$, $MmNi_{4.6}Fe_{0.4}$, $La_{0.5}Ce_{0.5}Ni_4Co$, and others in our country.

Due to the discovery and optimization of new deposits and the existence of current deposits, the demand for nickel, copper, and cobalt for rare earth-based intermetallic alloys is fully met. For example, KAZMinerals is a major operator of three deposits (Bozshakol, Aktogay, Bozymchak (Kyrgyzstan)) with copper (0.30–0.33% in ore), gold (0.15–0.25 g/t), nickel, and cobalt [177]. In 2022, the mining and processing of nickel-cobalt ores from the Bugetkol deposit (NiO – 1.76%, Co – 0.11%) was established using percolation leaching and subsequent concentration and separation by ion exchange [178].

According to the Institute of Geological Sciences [179], rare earth elements are contained in the titanium-rare earth deposit Kundybay (25 thousand tons of approved reserves of REM oxides and 49 million tons with REE content – 0.051%) [180], rare metals – Zhanet, South Zhaur, Koktenkol, Upper Espe, Karasu, as well as in the phosphorite massif Karatau. Significant amounts of REE and rare metals are contained in uranium deposits. There are other raw material sources of their production. According to the latest data [181], on the new REM deposit "Akbulak" in Kostanay region geological exploration works by the domestic company "KazGeology" together with "Cove Capital" on industrial production of REM in our country have begun. According to preliminary data resources contain 380 thousand tons of rare metals and REM, namely yttrium, cerium, thulium, zirconium, lutetium, tin and others.

It should be noted that, despite the lack of enterprises for obtaining finished REM products, there are enough large deposits in Kazakhstan that can meet the demand for the production of intermetallic alloys for hydrogen storage based on AB_5 alloys.

In conclusion, it is important to note that successful industrial production of intermetallic compounds for hydrogen storage, such as MgH_2, TiFe, and $LaNi_5$, requires overcoming a range of technological and economic barriers. Starting with MgH_2, it necessitates high temperatures (673–723 K) for hydrogenation and dehydrogenation, which increases energy and equipment costs. Additionally, MgH_2 is prone to oxidation when exposed to air, reducing hydrogenation rates. To address these issues, methods such as alloying with transition metals and applying protective coatings are employed. Moving on to TiFe, it requires high-purity raw materials and a multistep process for synthesis, complicating industrial production and raising costs. To enhance TiFe activation and reduce plateau pressures, alloying with elements like Mn, Co, and V is used. As for $LaNi_5$, its production involves expensive rare earth metals, such as lanthanum, and specialized melting and milling equipment. Modifying $LaNi_5$ with elements such as Al, Co, and Mn can improve its operational characteristics and extend its lifespan.

Moreover, significant investments in this sector are crucial, along with attracting international experts to transfer knowledge and technologies. Training local specialists in hydrogen storage and the development of intermetallic compounds is also critically important for success in this field. Thus, successful implementation of these compounds in industrial production is achievable through the use of advanced synthesis methods, enhancement of kinetic properties, development of cost-effective technologies, and engagement of international expertise. This will enable Kazakhstan to leverage its rich mineral resources and become a leader in the production of materials for hydrogen energy.

5. Conclusion

The issue of hydrogen storage is a major obstacle to the widespread adoption of hydrogen energy. Existing storage methods, such as compression and liquefaction of hydrogen, have significant drawbacks, including high energy and resource costs, the need for specialized equipment, and a substantial risk of leaks and explosions. These factors greatly complicate the practical application of these technologies.

Against this backdrop, solid-state hydrogen storage emerges as the most promising and safe direction. Metal hydrides, complex hydrides, and adsorption materials based on carbon and metal-organic frameworks (MOFs) exhibit high hydrogen storage density, stability, and relatively low operating temperatures and pressures. These properties make solid-state materials preferable for creating safe and efficient hydrogen storage systems. In this context, particular attention should be paid to absorption intermetallic compounds such as MgH_2, TiFe, and $LaNi_5$, and their modifications. These materials have several advantages, including high hydrogen storage density, stability, and the ability for multiple uses.

Kazakhstan, possessing significant reserves of mineral ores, including rare earth, precious, and heavy metals, has unique opportunities for the development of intermetallic compounds for hydrogen storage. The presence of the country's mineral resource base creates prerequisites for the successful implementation of projects to create solid-state materials for hydrogen energy. However, to achieve these goals, several challenges must be overcome. These include high purity requirements for raw materials, complex synthesis methods, the need for specialized equipment and technology, and a high level of technical training for specialists.

Special attention should be given to significant investments in this sector, which are necessary for the development of hydrogen storage infrastructure and technologies. Attracting international experts to transfer experience and advanced technologies is also critically important. Training local specialists and creating local research centers will allow Kazakhstan not only to utilize its rich resources but also to develop a sustainable and innovative hydrogen energy industry.

The development of comprehensive mineral raw material processing and the implementation of modern technologies for the production of intermetallic compounds, such as MgH_2, TiFe, and $LaNi_5$, will not only strengthen the country's economic potential but also achieve sustainable development goals aimed at reducing carbon emissions and transitioning to alternative energy sources. Thus, Kazakhstan has all the necessary resources and potential to become one of the leading producers and exporters of hydrogen technologies, contributing to global decarbonization and the development of the hydrogen economy.

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