

A Proposal for Water Transportation by a Hydrogen Energy System — A Feasibility Study for Kazakhstan —

by

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Abstract

This study examines the use of hydrogen as an energy carrier for spreading renewable energy and mitigating environmental problems, and proposes a system for carrying clean water together with hydrogen. Practical simulations were carried out assuming the present conditions of Kazakhstan. The capital and most other large cities are located both far from clean water sources, and areas with plenty of sunshine. The proposed model consists of hydrogen generation by solar-powered electrolysis, transportation of hydrogen by railways and electric power generation using fuel cells in cities. The fuel cells also generate clean liquid water.

This paper proposes a hydrogen transportation system by railway, where Ti-based hydrogen storage alloys fabricated with readily available metals in Kazakhstan are used. The railway is the most practical means of transportation compared to other methods in terms of utilities, economy, environment and time.

Keywords: Kazakhstan, Hydrogen energy system, Hydrogen storage alloys, Ti-based alloys, LCA

1. Introduction

Along with the spread of activities on SDGs, the realization of a sustainable society is expanding worldwide. It is necessary to realize the improvement of people's QOL as soon as possible in order to break away from the social system based on the massive consumption of fossil energy resources.

Kazakhstan is a country located in the central part of the Eurasian continent and is rich in coal, oil, and other mineral resources. Most cities have developed along the historical Silk Road. The existing social infrastructure was established under the Soviet Union in the 20th century and is still used today despite its aged condition.

In terms of the water supply system, each large city obtains water from the nearest river using aged facilities. However, the amount of incoming river water is reduced due

to its utilization for neighboring countries' agriculture. Moreover, it arrives at the borders of Kazakhstan already polluted.

Not only industrial emissions and agricultural pesticides are causes of polluted tap water, but also nuclear pollution from nuclear tests during the Cold War in north-eastern to middle-southern parts of the country.

Under these conditions, the drinking water supply issue is a significant problem, including how to supply drinking water from limited water resources to large urban areas. This proposal is unique and rarely considered in Japan, an island with plenty of clean water.

This study proposes hydrogen energy as an alternate, new, sustainable, affordable, and reliable energy, as well as a drinking water supply source by utilizing hydrogen energy using fuel cells. As a first feasibility study, we propose a simple hydrogen energy system model as a solution for the water supply issues in Kazakhstan by utilizing the existing infrastructure as much as possible while considering cost and realizing period.

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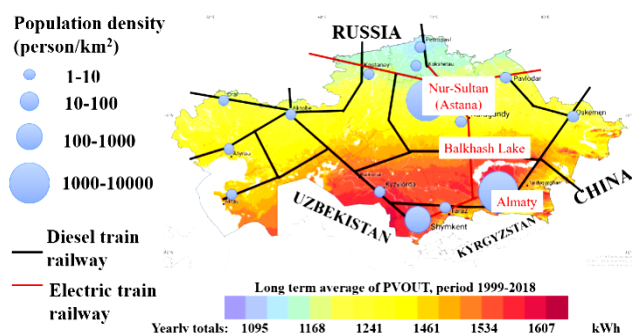


Fig.1 Solar radiation, population density, railway map of Kazakhstan made based on references ¹⁻³⁾.

2. Background

In Fig.1 the distribution of population and solar radiation, densities are shown. Suitable drinking water may be obtained from Balkhash Lake, one of the limited clean water resources located in the southeast area of the country. Large cities of Kazakhstan are Almaty and Nur-Sultan (Astana), both with a population of about 1 million. In Fig.1 railways connecting areas and cities are also shown.

2.1 Energy consumption and resources

Kazakhstan aims to reduce dependence on fossil fuels for its energy utilization and develop a sustainable society by utilizing renewable energy.

Kazakhstan's energy production covers more than twice its energy demand, and the energy self-sufficiency rate is around 200 % ⁴⁾. Coal represents almost 50 % of Kazakhstan's primary energy supply, and it is utilized for domestic energy consumption, which is more than 70 % of the total power generation ⁴⁾. However, the current existing infrastructure is disintegrating, and new construction is unfeasible because of a complicated political situation.

The potential of solar power is high in this country. For example, Kazakhstan's southern and central regions have high insolation that could be suitable for solar power with daylight hours of 2200-3000 h/year and sunlight $1.3-1.7 \times 10^3$ kWh/m² annually (Fig.1) ¹⁾. Solar power could reach the range of $2.5-3.5 \times 10^{12}$ kWh per year, which is 25 times larger than the present total production of electricity, and would use only half of the country's total surface area.

2.2 Water consumption and supply

In exchange for plentiful sunshine, water resources in Kazakhstan are not abundant, because of climate characteristics such as deficient annual precipitation and desertification. The country's rainfall amount is not large, with the average annual precipitation estimated around 250 mm.

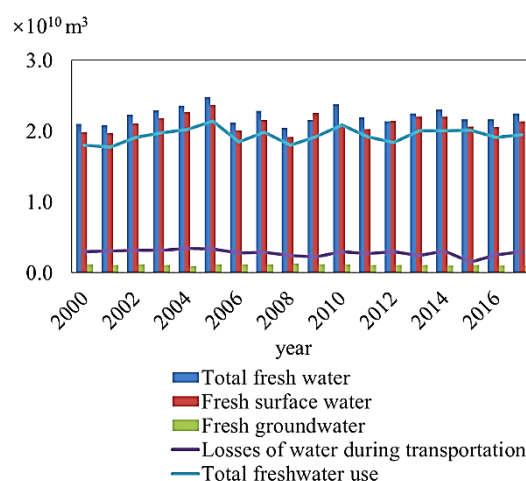


Fig. 2 Total freshwater abstracted, total freshwater use and losses of water during transportation ⁴⁾.

In Kazakhstan, water resources are mainly concentrated in eight major rivers and three big lakes (the Caspian Sea, Aral Sea, and Balkhash Lake). Balkhash Lake is the primary source of freshwater.

Water availability across these major basins is distributed unevenly, and approximately 45 % of the water in the country inflows from neighboring countries such as Russia, China, Kyrgyzstan, and Uzbekistan. Inflows are expected to decrease due to increased water withdrawals for hydroelectricity generation and irrigation in Central Asia and China ⁵⁾.

Annual freshwater withdrawals total around 2.3×10^4 m³/year. Almost all freshwater is harvested from surface water because of a lack of groundwater. Consequently, surface water needs to be transported, and, unfortunately, 12 % of it is lost during transport due to old structures (Fig.2) ⁴⁾.

The water supply service is relatively weak in terms of quantity and quality. A shortage of high-quality drinking water is still acute in some regions, where households in remote areas have the water delivered in water tanks and stored in individual reservoirs.

Moreover, tap water is not safe to drink in Kazakhstan, and around 30 % of consumers completely abandon it, preferring to buy bottled water. Hence, 9×10^5 m³ per year of bottled water is transported in large cities ⁶⁾.

The agriculture sector is the primary driver of water consumption in Kazakhstan (70 % of total consumption). The electricity industry and manufacturing are second large water consuming sectors at 20 % followed by households at 10 % ⁴⁾.

3. Hydrogen Energy System

In order to create a hydrogen energy system, we need a practical consideration of hydrogen production, storage, and utilization that does not have a significant impact on the

environment ⁷⁾.

For the realization and prosperity of hydrogen energy society, it is essential to recognize that its production method plays a very significant role in the level of environmental impacts. Hydrogen produced from water using renewable energy sources offers the prospect of long-term growth in full alignment with the need to protect the environment. It will be one of the most promising energy options for a sustainable future ⁸⁾. Cycling of hydrogen without CO₂ emissions can be achieved through the production of hydrogen by electrolysis and hydrogen consumption through the use of fuel cells.

Nowadays, the technologies for the production and use of hydrogen have been found, and efficiency problems have been identified. Also, to use hydrogen in practice, it is necessary to consider a reliable and stable method of storing and transporting it.

In this article, we focus on transporting and storing hydrogen, which is also a method for transporting water.

4. Hydrogen Transportation

Hydrogen can be transported by different means. Currently, the transport of compressed gaseous or liquid hydrogen by lorry to selected locations is the main option. A pipeline network is also an option for the general and largescale use of hydrogen as an energy source. However, pipelines require high initial investment levels and long-term construction. Design requirements for hydrogen pipelines are still evolving. Most hydrogen pipelines are designed to transport hydrogen only short distances, from the production facility to the end-user. Moreover, the hydrogen pipeline quickly develops leaks, requiring strict safety equipment and carries only about 80 % energy at the same pressure as natural gas ⁹⁾.

Hydrogen pipelines have problems with embrittlement, safety, and leaks. Hydrogen has an active electron, and therefore behaves somewhat like a halogen. For this reason, hydrogen pipes have to resist corrosion in the ground. The problem is intensified because hydrogen can easily migrate into the crystal structure of most metals ¹⁰⁾.

Hydrogen storage alloys have attracted considerable attention because they are safe and efficient media for transporting hydrogen energy. Since hydrogen storage alloys are known to be heavy, they can be transported by rail, consequently increasing the amount of hydrogen that can be transported in the existing infrastructure.

An essential transport mode in Kazakhstan is railway transport, which connects the entire country (Fig. 1)³⁾. Trains account for 70 % of all cargo and passenger traffic, covering their world ranking rates and estimated cost ¹³⁾.

Table 1 Kazakhstan (KZ) reserves of metal resources with

Metal	World Ranking	Confirmed Reserves ($\times 10^7$ kg)	Cost (US\$/kg)	Global reserves (%)	Located part of KZ
Ti	10	2.40	4.8	0.1	East
Cr	2	38.2	5.1	30	West
Mn	4	63.5	2.0	25	Central
Fe	7	26.5	1.1	10	North

60 % of the country's territory. The load capacity of one freight car is $6\text{--}7 \times 10^4$ kg ¹¹⁾. Additionally, transportation by railway is attractive for its lower emission of CO₂, which is 2.53×10^{-10} kg-CO₂/kg·m (25.3g / ton·km) ¹²⁾.

Furthermore, the transportation of hydrogen by units is easy to carry to the required place, the required amount of electricity and water. If a fuel cell is attached to a locomotive, the train can supply energy by itself and distribute water along the rail lines.

5. Hydrogen Storage

As mentioned above, Kazakhstan has substantial natural and mineral resources. Specifically, Kazakhstan has 30 % of the global reserves of chrome ores, which is second globally, 25 % of manganese ores, 10 % of iron ores and is ranked tenth in the world in terms of titanium reserves ¹³⁾.

In this contribution, we consider utilizing those metals for hydrogen storage alloys as hydrogen carriers. In general, the titanium-based alloys are among the most promising materials for hydrogen storage ¹⁴⁾. Currently, practically useful hydrogen storage alloys are made from rare earth metals, rare resources and are very expensive. In Kazakhstan Ti, Cr, Fe, and Mn are abundant, and their prices are lower than rare earth metals (Table 1).

According to the literature, TiCrMn and TiFeMn alloys absorb reversibly about 1-1.5 wt% of hydrogen on average (Table 2) ¹⁵⁻¹⁹⁾. Alloys TiCrMn, TiFeMn are suitable as capable carriers for the transport of hydrogen energy in Kazakhstan.

We suggest preparing hydrogen storage alloy by mechanical alloying (MA) technique, a more suitable manufacturing method for alloys' mass production. MA can synthesize various non-equilibrium alloys, so it has been widely applied to modify properties of a hydrogen storage alloy ²⁰⁾. Compared with the arc melting (AM) method, the MA method enables synthesizing at low power for a long time. Moreover, since at the same vapor pressure 133 Pa, the temperature of Mn (1522 K) is lower than the other metals Cr (1968 K), Fe (2063 K), Ti (2464 K), it can be prepared by

Table 2 Hydrogen storage characteristics (Dissociation Temperature and pressure and H capacity), of Ti-based alloys prepared by arc melting (AM) and mechanical alloying (MA).

Alloys	T (K)	P (MPa)	H (wt%)	Preparation	Ref.
Ti _{1.1} CrMn	296	3.3	1.8	AM	¹⁵⁾
TiCrMn _{0.8}	304	1	1.98	AM	¹⁶⁾
Ti _{1.1} CrMn	273	1.2	1.61	AM	¹⁷⁾
TiFe _{0.8} Mn _{0.2}	298	1.5	1.65	AM	¹⁸⁾
TiFe _{0.9} Mn _{0.1}	295	0.8	1.5	AM	¹⁹⁾
TiFe _{0.85} Mn _{0.15}	298	1.5	1.2	MA	²⁰⁾

MA at room temperature ²¹⁾.

We have already investigated the preparation of alloys by MA in our previous work ²²⁾. Our succeeding work is related to improving the hydrogenation characteristics of these alloys.

6. Hydrogen Energy System in Kazakhstan

The overall hydrogen system consists of solar energy, an electrolyzer for hydrogen production, alloys for hydrogen storage, trains for transportation, and fuel cells for utilization.

First, we consider the amount of hydrogen per capita as the necessary energy and the amount of water as the amount of hydrogen needed to be utilized.

The energy consumption per capita is 5.0×10^3 kWh/year ($1 \text{ kWh} = 1 \text{ J/s} \times 3600 \text{ s} = 3.6 \times 10^6 \text{ J}$) and clean drinking water consumption per capita of $1 \text{ m}^3/\text{year}$ in Kazakhstan ⁴⁾. We summarize the appropriately quantified analysis of the Hydrogen Energy System in Kazakhstan based on these amounts.

Corresponding hydrogen amount is calculated as follows of formula (1). We use Lower Heating Values (LHV) of hydrogen, which is 6.7×10^{-2} kWh/mol. (The lower heating value is the amount of heat released during the complete combustion of fuel without condensation of water vapor ²³⁾. If it condensed, available energy is denoted as Higher Heating Values(HHV))

$$E_{\text{per capita}} (5 \times 10^3 \text{ kWh}) / \text{LHV}_{\text{hydrogen}} (6.7 \times 10^{-2} \text{ kWh/mol}) = 7.4 \times 10^4 \text{ mol H}_2 \quad (1)$$

$7.4 \times 10^4 \text{ mol H}_2$ produces $7.4 \times 10^4 \text{ mol}$ water, which is $1.3 \text{ m}^3/\text{year}$ and provides the necessary amount of hydrogen to required electricity $5 \times 10^3 \text{ kWh/capita}$.

Secondly, we determine the required energy to produce this amount of hydrogen. We calculated the necessary energy from electrolyzer, solar power, and surface area based on efficiency, 70 %, and 16 %, respectively. Calculated results

Table 3 Calculation to produce the required energy and water by hydrogen/capita.

Necessary water to produce hydrogen	$1.3 \text{ m}^3/\text{year}$
Solar power and surface area (16 % energy efficiency)	$5.2 \times 10^4 \text{ kWh/year}$ 34.8 m^2
Energy from electrolyzer (70 % energy efficiency)	$8.3 \times 10^3 \text{ kWh/year}$
Necessary energy to produce hydrogen	$5.8 \times 10^3 \text{ kWh/year}$
Produced hydrogen	$7.4 \times 10^4 \text{ mol /year}$
Energy consumption per capita	5000 kWh/year
Produced water	$1.3 \text{ m}^3/\text{year}$

are shown in Table 3. We obtain $1.3 \text{ m}^3/\text{year/capita}$ water by a fuel cell, which ensures the necessary water $1 \text{ m}^3/\text{year}$ per capita.

We consider the fuel cell (50 % efficiency for electricity) and simulated hydrogen energy system for the capital city Nur-Sultan, where the population is growing, and consumption of energy and water is increasing (Fig. 3) ²⁾.

In this paper, the hydrogen energy system was modeled for a city with a population of one million based on a calculation per capita. They will consume hydrogen, which is generated by the electrolysis method from Balkhash Lake by utilizing solar power and transported by hydrogen storage alloys via railway. The solar panel area will be located near Balkhash Lake because of high solar radiation in the South and Central part of Kazakhstan.

This lake was chosen because of the location and quality of water. Moreover, Balkhash Lake is the primary water resource in domestic supply. The volume of water in Balkhash Lake is $1.1 \times 10^{11} \text{ m}^3$. The distance between Balkhash and Nur-Sultan is around $6 \times 10^5 \text{ m}$ ²⁴⁾.

We assume the weight of transported hydrogen storage alloy per wagon is $5.4 \times 10^4 \text{ kg}$ with 1.5 wt% of hydrogen. The hydrogen capacity per wagon is $4.1 \times 10^5 \text{ mol}$.

If a regular train is composed of 50 wagons, $2.04 \times 10^7 \text{ mol H}_2$ will be transported. If a train transports it 10 times per day, they transport $2.04 \times 10^8 \text{ mol}$ of H_2/day and $7.4 \times 10^{10} \text{ mol /year}$. Approximately $3 \times 10^7 \text{ kg/year}$ of the alloy will be used. Finally, one million people are provided with water and 0.4 million people with electricity by utilizing fuel cells. These values are summarized in Fig. 3.

7. LCA of Hydrogen Energy System for Kazakhstan

Life Cycle Assessment is a systematic tool to analyze the environmental impact of a product through all stages of its life cycle, from the extraction of resources to the

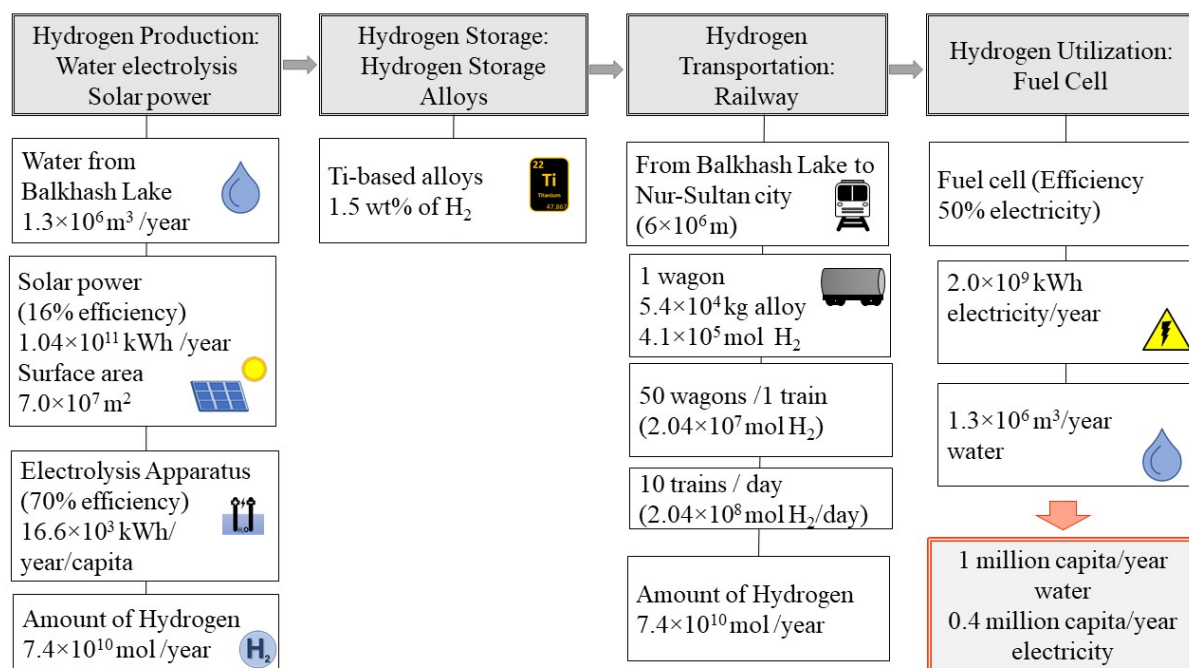


Fig.3 Hydrogen Energy System (HES) for the capital city of Kazakhstan

(calculation based for 1 million capita with 5000 kWh/year/capita electricity and corresponding water consumption).

production of materials, parts and the products itself, and its management after it is discarded, either by reuse, recycling or final disposal. LCA compiles and evaluates the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle.

IDEA (Inventory Database for Environmental Analysis), a Japanese database that mainly uses national and some international statistics as its data source and aims to model the environmental impacts ²⁵⁾. Unfortunately, the data for Kazakhstan is not available. To compare and see the general environmental impact, IDEA v2 was chosen.

We took into account the available CO₂ emissions from each process in this system. Based on IDEA soft dates and other references, we calculated considering the values listed in Table 4 the CO₂ emissions for the Hydrogen Energy System in Kazakhstan, which was more than 20 times less than present CO₂ emissions for electricity coal.

8. Conclusion

This contribution considered the energy and water situation in Kazakhstan, which is currently significantly dependent on fossil fuels, despite the high potential of renewable energy sources, especially the potential of solar energy. Due in part to the abundance of sunshine, there are not many water resources in Kazakhstan.

Thus, half of the water resources inflow from neighboring countries. Depending on the transboundary rivers, the lack of groundwater, and losses during the transportation of surface water make this problem more serious.

Table 4 CO₂ emissions of corresponding process delivered form calculation using IDEA data ²⁵⁾.

Process	CO ₂ (kg)	Consumption/ year (for 10 ⁶ capita)	CO ₂ (kg) for HES
Consumption of solar power 1kWh	5×10^{-2}	1.04×10^{11} kWh /year	5.2×10^8
Production of Ti 1kg	9.2×10^{-5}	10^7 kg	9.2×10^2
Production of Cr 1kg	5.9×10^{-3}	10^7 kg	5.9×10^4
Production of Mn 1kg	5.9×10^{-3}	10^7 kg	5.9×10^4
Production of Fe 1kg	1.1×10^{-1}	10^7 kg	1.1×10^6
Ball milling 1000h / 10^5 kg ²⁶⁾	7.2×10^2	3×10^7 kg	2.2×10^4
Freight train 10^3 m/ 10^3 kg ²⁷⁾	2.5×10^{-2}	6×10^5 m/ 3×10^7 kg	1.5×10^8
Fuel-cell	0	2.0×10^9 kWh	0
Total for HES in KZ			6.7×10^8
Present electricity	3.5×10^{-1} /kWh	5×10^9 kWh	1.4×10^{10}

This paper supposes the role of the hydrogen energy system in Kazakhstan for water supply, renewable energy distribution, and reduction of greenhouse gas emissions. Transportation of water can be driven by the production of hydrogen through electrolysis and the consumption of hydrogen through the use of fuel cells, as proposed in the frame of the hydrogen energy system. We revealed that the required 5000 kWh/year electricity and 1 m³/year water are obtained by feasible hydrogen transportation.

The system is also capable of satisfying drinking water requirements, and society can become practically self-sufficient. The LCA result confirms that hydrogen is considered to be an ideal energy carrier in the future and can play a considerable role in the energy system of Kazakhstan.

In the future, the transportation possibilities of the fuel cell by train and utilization of fuel cells will be possible not only for large cities, but also for rural areas, and gives a significant opportunity for water supply. Transportation of hydrogen by storage alloys via railways allows the export of energy and water to neighboring countries. The water supply system considered here can be extended to other countries with water scarcity problems.

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