Pathway towards sustainable water use for hydrogen production through water electrolysis.

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The global demand for hydrogen is escalating rapidly as world leaders endeavor to address the urgent challenge of climate change by shifting away from non-renewable energy sources. Nevertheless, the production of renewable hydrogen presents a persistent challenge, although hydrogen electrolysis emerges as a prominent solution. A key challenge faced by policymakers worldwide is ensuring the sustainable procurement of water for hydrogen production through electrolysis. Hence, this comprehensive study offers a thorough examination of water utilization for hydrogen production across major global regions, while providing region-specific recommendations for effective management. This study contributes to enhancing the sustainability of hydrogen production and addresses a significant gap in previous research by comprehensively addressing the water sourcing challenge for hydrogen from both global and regional perspectives. By conducting rigorous calculations and qualitative analysis, the findings of this study demonstrate that water sourcing should not be a significant cause for concern, as the water demand for hydrogen production is comparatively minimal in relation to other water-intensive sectors. However, countries facing high water stress are advised to consider alternative strategies such as seawater desalination or importing hydrogen from nations with abundant water resources.

Introduction

As the global population continues to grow and economies expand, the demand for energy is expected to surge in many countries. Global energy consumption has already been on an upward trajectory for more than 50 years[1]. According to the U.S. Energy Information Administration (EIA), global energy consumption is projected to increase by nearly 50% between 2018 and 2050[2]. As a result, the development of sustainable and renewable sources of energy has become imperative for global leaders to achieve global decarbonization and to meet sustainable development goals such as Paris Agreement targets which aims to limit temperature increase to well below 2°C above pre-industrial levels as they seek to tackle climate change[3]. Currently, only 30% of the world's electricity is generated through renewable sources[4]. Although mainstream renewable energy sources such as solar, wind, and hydroelectricity offer promising alternatives to conventional energy sources, they are limited by several factors such as cost compared to conventional sources and regional availability[5].

Renewable energy sources have become an essential focus for global leaders and scientists in the fight against climate change. One renewable energy source that has recently garnered significant interest is hydrogen, which is considered as a promising energy vector to decarbonize current fossil-based energy systems. Hydrogen has a wide range of potential uses that make it an attractive option for the energy industry. It can be stored as a fuel and used to distribute heat and power during transportation, replacing fossil fuels. Additionally, it can act as a medium for storing electricity, solving the problem of energy intermittency. Moreover, hydrogen can be used in fuel cells to generate sustainable energy for transport and power sectors, which could potentially revolutionize the energy industry and pave the way for sustainable energy systems. Most importantly, hydrogen does not produce any carbon dioxide when burned, making it environmentally friendly[6].

While hydrogen is a promising renewable energy source, its production requires energy from another source, making its environmental impact dependent on the energy source used for production. During the 1920s, hydrogen was produced using an electrochemical process called alkaline electrolysis. However, the impurities produced during the process led to it being displaced by a new process in the 1970s, namely the production of hydrogen through natural gas. Almost half of the hydrogen produced in 2021 was derived from natural gas[7]. The drawback of this new method is that it creates a significant amount of greenhouse gases such as CO2, making it an environmental challenge. To resolve this issue, a new alternative for green hydrogen production has emerged in the form of water electrolysis, which generates only a small amount of greenhouse gases. If all hydrogen required by 2050 were green hydrogen rather than produced through natural gas, 1.2 gigatons of CO2 emissions would be reduced, which cumulates to 8 percent of the global budget to limit global warming to

1.5°C[8]. The Polymer Electrolyte Membrane, (PEM) system is the main electrolyzer used to produce hydrogen today. This system is preferred due to its compactness and high efficiency. Unlike alkaline electrolysis, which uses corrosive potassium hydroxide electrolytes, the PEM system runs on pure water, eliminating the need for electrolyte recycling. During operation, filtered, deionized water decomposes into oxygen and protons(H+) at the anode, and protons move across the membrane to the cathode and reduced to hydrogen gas (Figure 1, PEM Electrolyzer Unit)[9,10].

The key to hydrogen production through water electrolysis system is sourcing a sustainable pure water[12]. With the demand for hydrogen increasing, there is bound to be a growing demand for a water supply as well. At the same time, good quality water is also subject to demand from a range of competing sectors ranging from commercial to residential uses. This can be a problem for regions with a high-water stress, a problem which is worsened by climate change. Therefore, it is imperative for policy-makers to design policies and regulations that takes into account sustainable water supply and balance the demand for hydrogen production with other sectors.

One way to solve the challenge for regions without a constant, stable supply of pure water is seawater desalination. The major desalination technology, which has seen development over the years, is seawater reverse osmosis (SWRO). Reverse osmosis is a process that demineralizes and deionizes saltwater by pressuring it through a semi-permeable membrane, which allows the passage of water molecules but not dissolved salt molecules. The SWRO plant (Figure 1, Desalination Unit) contains a reverse osmosis unit that can separate salt from seawater through a membrane barrier and pumping energy, producing pure water that can be used for electrolysis to produce hydrogen. This process of reverse osmosis is less energy intensive than the lifecycle costs of drawing and producing hydrogen from natural gas. However, it is also important to account for the cost of the desalination process as that can add greatly to the cost of hydrogen production[11].

In the context of a global transition towards increasing green hydrogen production, the sourcing of pure water will likely become an area of issue. Therefore, this work seeks to provide a global view on the sustainable water sourcing for hydrogen production and examine its potential strain on global water resources and thus provide insights for policymakers around the globe on a plan suitable for their country. This study seeks to tackle this issue with a hypothesis approach to show that water requirement for hydrogen production is minimal:

Primary Hypothesis

The water consumption required for hydrogen production through electrolysis will be a negligible proportion of the most global countries' total renewable water supply.

Null Hypothesis

The water consumption required for hydrogen production through electrolysis will constitute a significant proportion of most global countries' total renewable water supply. Analysis methods used in the paper:

Quantitative:

1. Calculation of water demand for hydrogen production through electrolysis as a percentage of total renewable water supply
2. Calculation of individual countries' water stress
3. Calculation of pipeline costs for transportation of seawater.

Qualitative:

1. Providing a global view of the issue of water sourcing for hydrogen production
2. Providing country specific recommendations based on statistics and literature.

Results

To disprove the null hypothesis and to provide guidance for each region on how to best leverage its available water resources for hydrogen production through electrolysis, it is crucial to obtain the expected hydrogen output for major countries worldwide in 2050 to then calculate the water demand for hydrogen. According to the data, China is projected to produce the largest amount of hydrogen, followed by Argentina and Russia. In general, countries with vast land masses and long coastlines are expected to generate more hydrogen than smaller nations in arid regions, such as Mauritania (Figure 2).

To determine whether water demand for hydrogen production constituted a large proportion of a country's renewable water supply, we calculated the percentage of renewable water supply necessary for hydrogen production. Our findings indicate that only three countries- Oman, Cyprus, and Saudi Arabia - require a higher percentage (3%, 5%, and 8.5%, respectively) of their total water supply for green hydrogen production (Figure 4). As seen, the water demand for hydrogen production represents a large proportion of a country's total

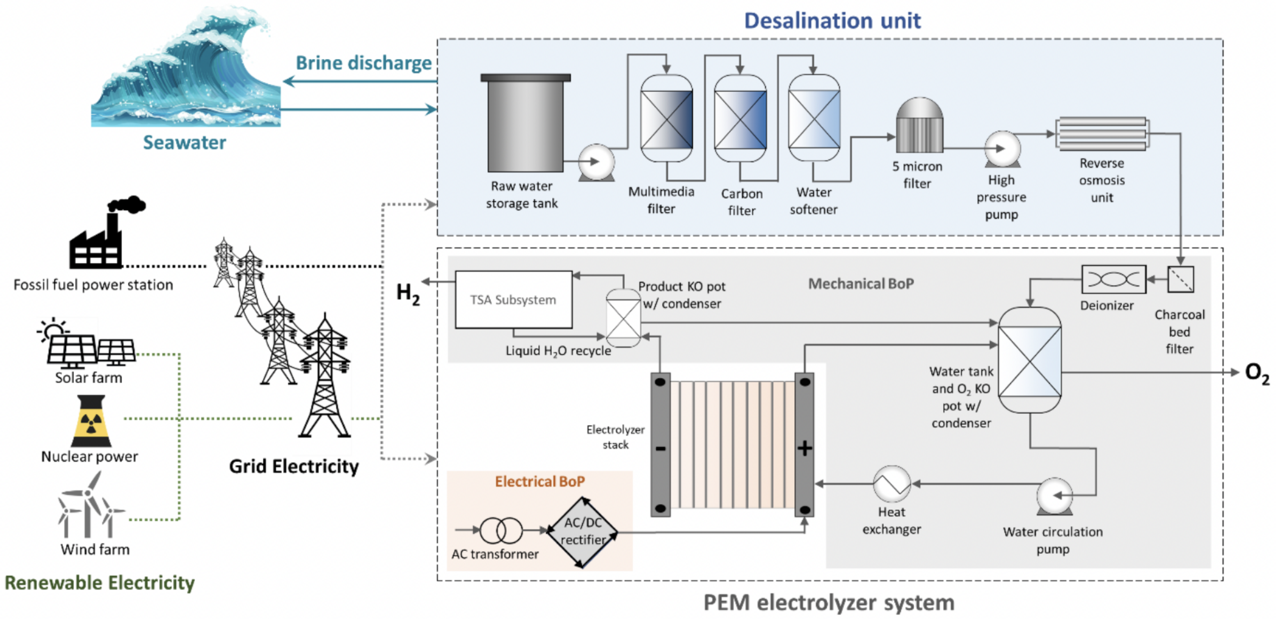


Fig. 1 Schematic of grid-powered SWRO-PEM system for 50 tons/day hydrogen production. Picture obtained from reference[11]

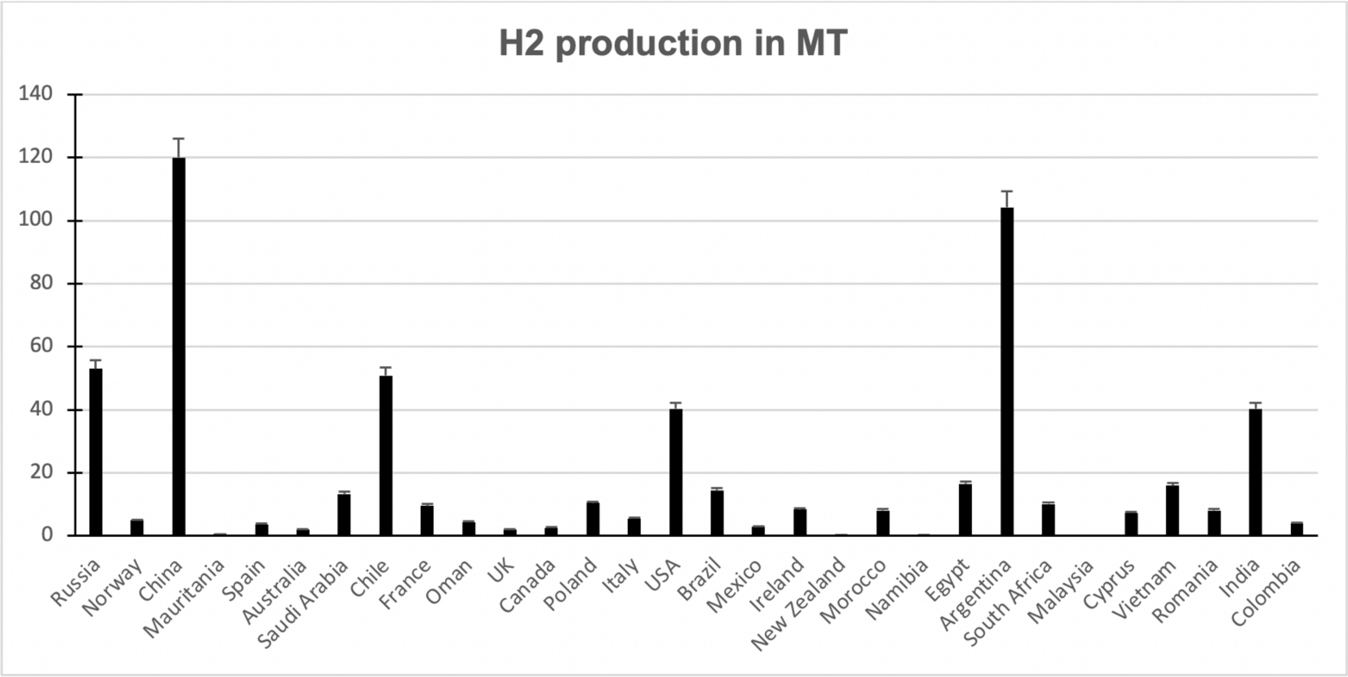


Fig. 2 H2 Production in MT of each country. (Error Bars -5%

water supply only in 3 countries out of the numerous countries included in this study (Figure 3), thus rejecting the null hypothesis.

To gain a more comprehensive understanding of each coun-

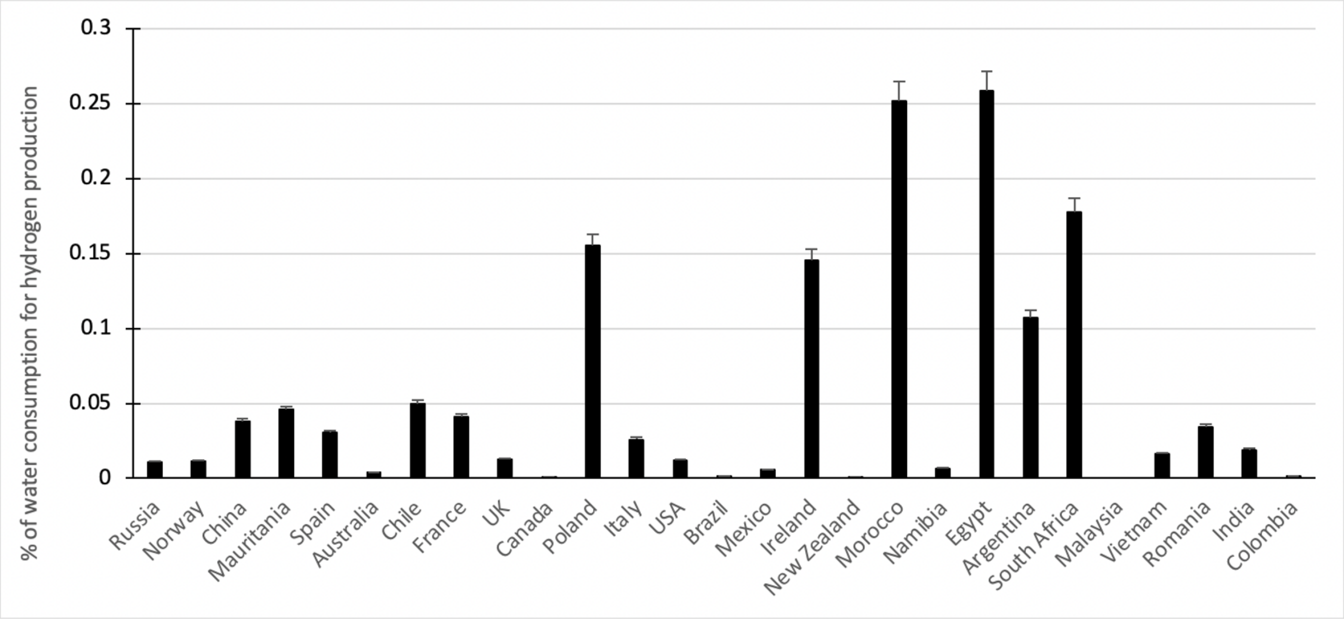


Fig. 3 water consumption for hydrogen production as a percentage of the total renewable supply of the country (Error Bar – 5%)

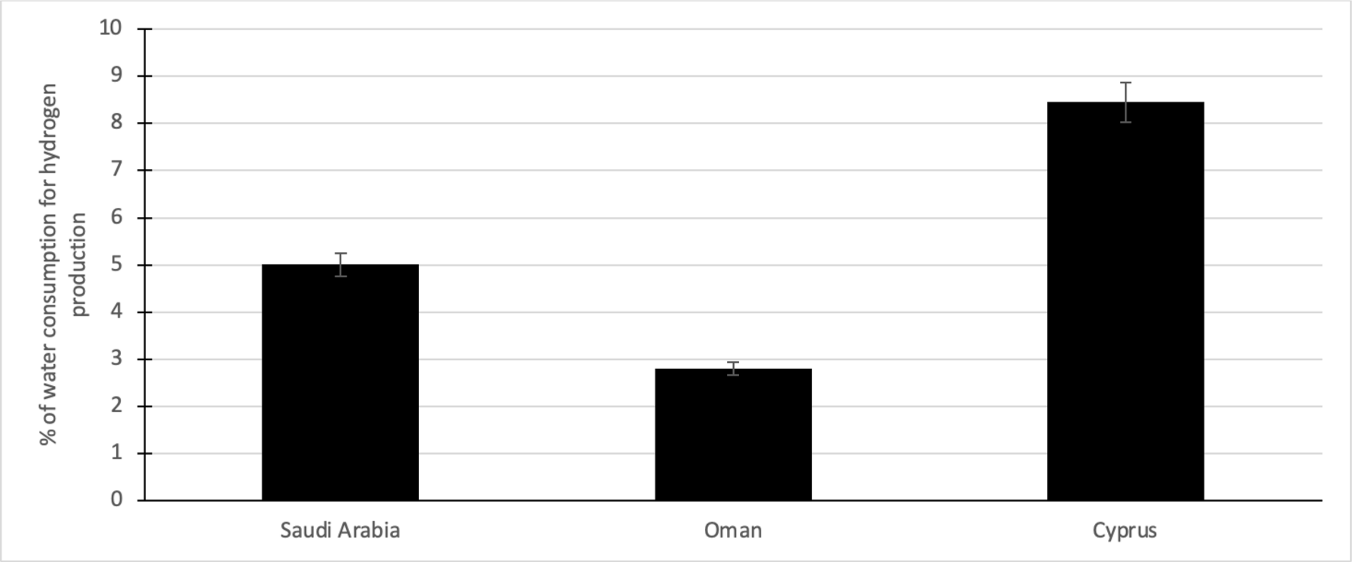


Fig. 4 water consumption for hydrogen production as a percentage of the total renewable supply of the country (Error Bar – 5%)

try's situation, we evaluated their water stress levels. According to the European Environmental Agency, "Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use[13]." For the quantitative analysis, the quality of water was not considered. It is important to take note that the water used for hydrogen production in insensitive to minor impurities compared to agricultural and human consumption. Furthermore, non-potable water can also be utilized for electrolysis[14]. Therefore, by limiting the definition of water stress, this study aims to highlight the potential for using otherwise unusable water for green hydrogen production. We classified the countries according to the water stress categories and found that nations such as Saudi Arabia and Egypt are among the most water-stressed. In general, inland arid countries with high populations tend to have higher water stress levels than countries located in humid areas with long coastlines and smaller populations (Figure 5).

In cases where direct water electrolysis is not feasible for a country due to a limited water supply, we considered the use of seawater desalination as an alternative method. One significant expense associated with seawater desalination is the cost of transporting seawater through pipelines. To estimate this cost for each country, we calculated the distance and diameter of the required pipelines based on its demand for water as well as the geography of the country, then using a formula to obtain the total construction and maintenance cost of the pipeline of a given diameter and length. According to the calculations, the average cost of building pipelines for a given country in the study was approximately four billion Euros, a considerable investment for any government. As expected, countries with large land areas or a high demand for hydrogen - such as China and Russia - faced correspondingly higher pipeline construction costs (Figure 6).

Discussion

Our study aimed to test our hypothesis that the water requirements for hydrogen production through electrolysis are minimal compared to the global water supply. Our findings support this hypothesis, showing that the water needed for hydrogen production in many countries represents only a small fraction of their total renewable water supply. However, due to local factors, some countries where the proportion of water required for hydrogen production is unexpectedly high might face higher production cost.

The minimal water requirement for hydrogen production in many parts of the world is not surprising. Firstly, a significant proportion of the water used during electrolysis is withdrawn rather than consumed, meaning that much of it is returned to its original source after being used. As a result, the net loss of water is greatly reduced. In fact, hydrogen production through electrolysis only requires 9kg of water per kg of hydrogen. Secondly, other sectors, such as agriculture, have much higher water requirements than hydrogen production. Agriculture alone accounts for 70% of the world's freshwater withdrawals and consumes 50 times more water than hydrogen production. Here, it is important that agricultural water demand varies by country depending on factors such as type of crop, population and weather. Countries such as China invest a lot in rice cultivation, which is one of the most water intensive crops and has a huge water demand for irrigation[15]. Therefore, the water use for hydrogen production is comparatively low, making it minimal. Thirdly, the increasing use of hydrogen has the potential to render fossil fuels obsolete, saving 10 billion m3 of freshwater that would have been used in fossil fuel extraction and processing. This would further reduce the net loss of water[12].

At the same time, water seasonality must be considered as well, as in most countries, water availability varies with season. This, compounded with the fact that the cost of transportation and storage of water is generally high, leads to a decrease in the supply of water compared to a country's whole renewable water resources and therefore sometimes a gap between supply and demand. As a result, countries should utitlize their existing resources as well as devise a plan to account for this seasonality.

Given this seasonality and slight nuance between different regions, another objective of this project is to provide a tailored analysis for each major region on a sustainable pathway for hydrogen production through water electrolysis. In this section, a customized review will be provided for each country.

China

China's abundant resources, vast land mass, and large demand are expected to make it the world's single biggest hydrogen producer, with a projected output of 120 million tons by 2050 (Figure 1). The amount of water required to produce this quantity of hydrogen only represents less than 0.05% of China's total renewable water resource. However, policymakers should be aware that China currently faces a 20% water stress, highlighting the importance of sustainable water management practices in the development of its hydrogen industry. Furthermore, China experiences seasonal rainfall variations partly due to monsoons, making the consideration for a season-based approach to hydrogen production[16]. This season-based approach for hydrogen production also allows time for the water used for electrolysis to be recycled for irrigation in rice fields. As previously mentioned, unlike irrigation where the water is consumed, water used for electrolysis can be returned to the environment.

China has made significant strides in developing renewable energy sources such as solar and wind. However, there is still a need to focus on complementary hydrogen energy systems, given the lack of funding and regulations in this area[17]. With the potential to become the world's largest hydrogen producer by 2050 and a responsibility to mitigate climate change, China should consider investing in the development and implementation of technology related to hydrogen production through water electrolysis. This could help to reduce greenhouse gas emissions and dependence on fossil fuels, while also taking into account the country's current water stress level of 20%.

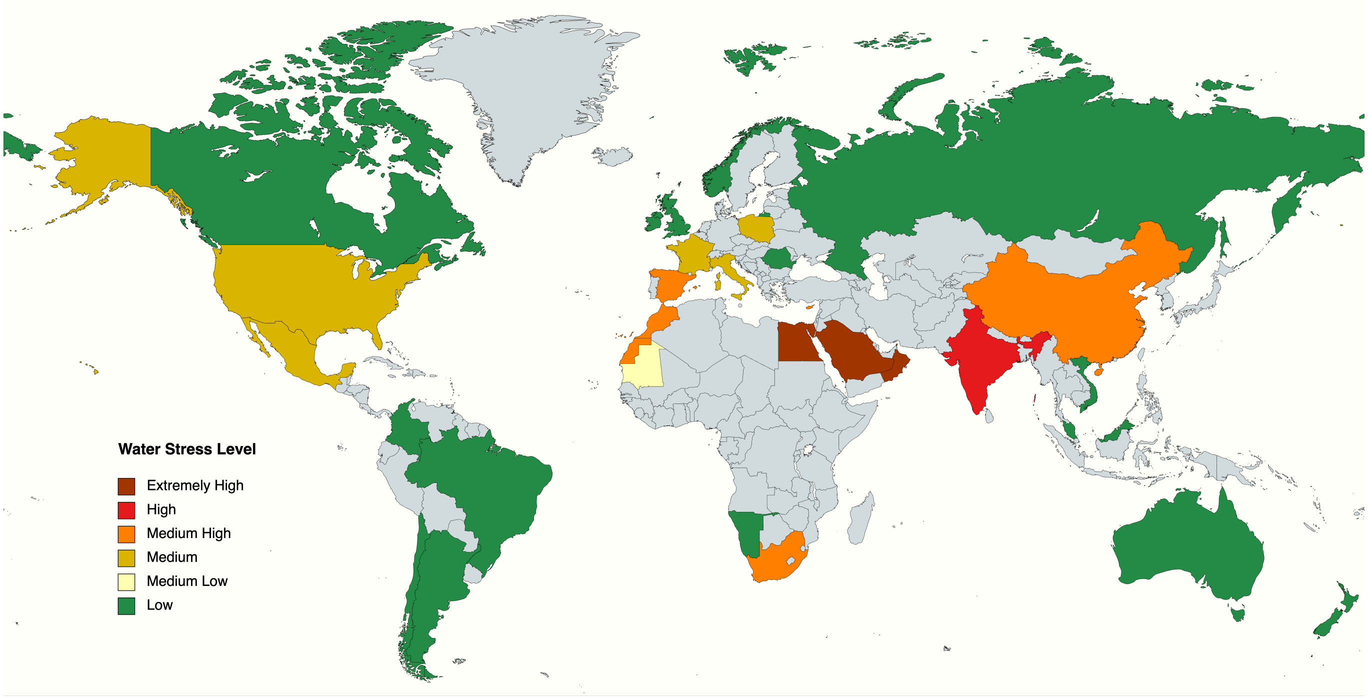


Fig. 5

United States

As the United States aims to transition to a net-zero carbon emissions country by 2050, it is poised to become a major producer of hydrogen in the future. The country boasts ample resources, including expertise, technology, financial capability, and a large water supply, to accomplish this goal. As a global leader, the US has an opportunity to lead the world's transition to hydrogen energy through policies and by supporting other countries in their efforts to adopt this sustainable energy source[18].

Argentina

Despite its relatively small size, Argentina has enormous potential for hydrogen production. Every province in the country has one department where the potential for renewable hydrogen production is ten times the demand. As per the results, Argentina has low water stress, and producing hydrogen requires only 0.001% of its total water supply (Figure 3). This potential is on par with that of the United States. Given this enormous potential, Argentina should heavily invest in renewable hydrogen and consider exporting it to other countries in need. The country's extensive natural pipeline system could also potentially aid in the storage and transportation of water and hydrogen[19].

Russia

Russia, known for its abundant natural resources, has significant potential for hydrogen production due to its vast water supply and low water stress. With the fourth largest shoreline in the world[20], Russia could leverage its coastal resources for hydrogen production. However, the transportation of hydrogen may pose challenges given Russia's enormous size. Transporting water from the shoreline to the country's center could cost up to 30 billion euros (Figure 6). To overcome this obstacle, Russia could re-purpose its existing pipeline infrastructure for the transportation of hydrogen or renewable water and invest in the development and adoption of renewable hydrogen energy technologies[21].

Europe

While none of the individual European countries investigated are projected to have high hydrogen production in the future, Eastern European countries like Poland and Romania are expected to play a significant role in renewable production, while Western European countries like Italy are projected to play a relatively smaller role. However, when all European countries are combined, the amount of hydrogen produced is actually substantial.

Europe, a highly developed and interconnected continent,

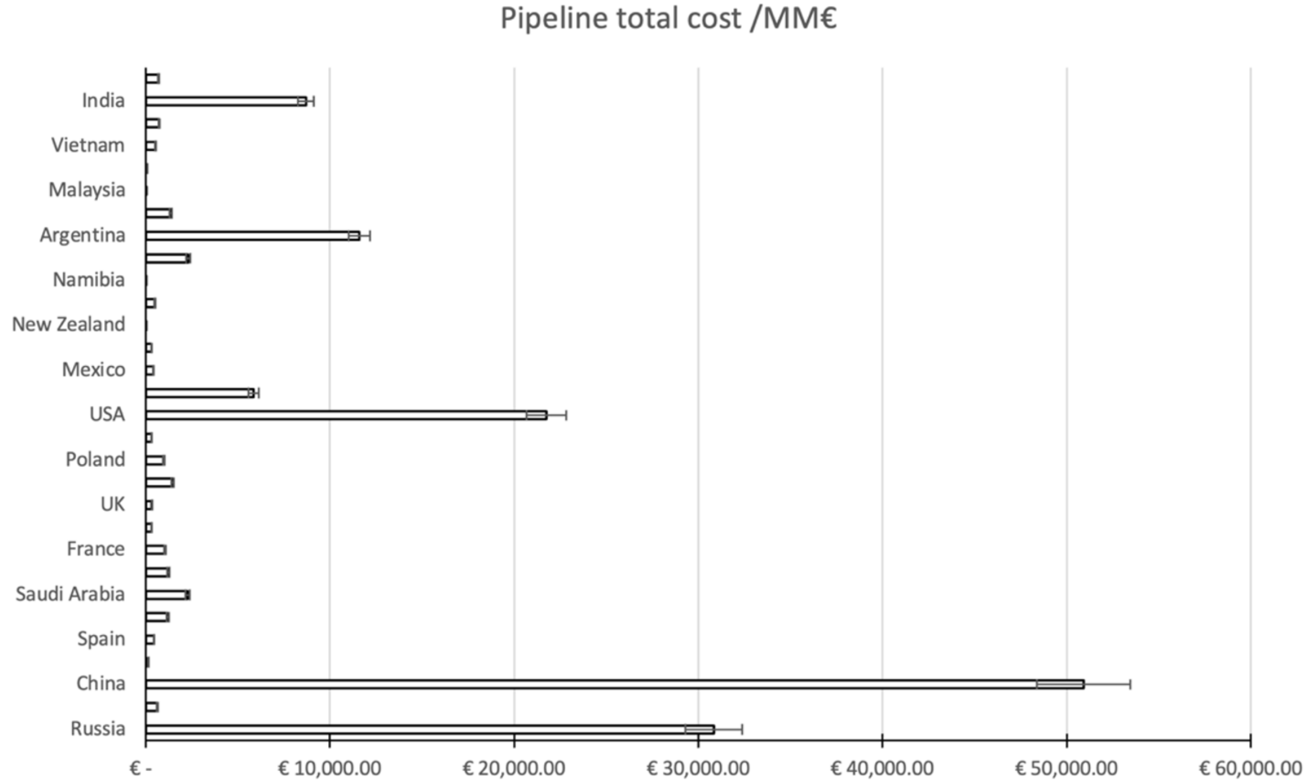


Fig. 6 Total Pipeline Cost in Euros for Each Country (Error Bar – 5%)

is well-suited for the implementation of renewable hydrogen production through electrolysis and that would decrease the storage and transportation cost of water resources. Therefore, it is crucial for countries like the UK, with low water stress, high levels of development, and relatively low hydrogen production, to allocate sufficient funds to support Europe's transition towards renewable energy. By doing so, Europe can potentially become a global leader in hydrogen production and pave the way for a sustainable future.

Africa

Africa, historically an area of high water stress, continues to face this challenge, as reflected in the results of the investigation. Producing hydrogen through electrolysis will require a significant portion of the region's already limited water supply. For instance, both Egypt and Morocco would consume nearly 0.25% of their renewable water supply to produce hydrogen (Figure 3). Furthermore, the distinct dry and wet seasons in Africa would lead to an inconsistent water supply[22]. Countries such as Egypt also need to be wary of balancing water use between water irrigation for crops and hydrogen production. Thus, instead of direct water electrolysis, African countries could explore the alternative of seawater desalination. Coastal countries such as Morocco and Mauritania have enormous potential in this area. Egypt would need to invest 2 billion Euros in pipelines, equivalent to 0.4% of its total GDP, to transport seawater to different regions across the country(Figure 6). Similarly, Morocco and South Africa would have to allocate 0.35% and 0.2% of their GDP[23], respectively, towards desalination (Figure 6). Therefore, policymakers in African countries should consider seawater desalination as a viable alternative to green hydrogen production.

Middle East

The Middle East faces some of the highest levels of water stress globally, with producing hydrogen using a country's renewable water resource potentially using up to 5% of Egypt's water supply and 3% of Oman's (Figure 4). This poses a challenge for transitioning away from non-renewable energy production, especially given the region's abundance of fossil fuels. To support sustainable hydrogen production using seawater desalination, policymakers from other countries must provide the necessary technological and financial support to Middle Eastern countries. Moreover, countries that produce excess green hydrogen could explore the option of exporting it to the Middle East to meet the region's demand; however, the transportation cost must be considered.

Impact

This study advanced the understanding of water use in hydrogen production through electrolysis through calculations and analysis. This study was able to shed light on how global policymakers should make use of water resources effectively for a green future. By understanding the water resources needed, countries can better plan their transition into renewable energy. Additionally, this study highlights the need for sustainable water management in water stressed regions and the need for global cooperation.

Inference / Conclusions

This study reveals that water supply should not be a significant concern for policymakers when it comes to producing green hydrogen. However, it also reveals that nations in water-scarce regions should seek alternative water sourcing methods such as importation and seawater desalination. The need for country-specific tailored strategies for hydrogen production due to differing geographic and economic challenges is underscored.

Limitations

It is important to acknowledge that this study may not account for all factors and nuances related to green hydrogen production, which could result in imprecise conclusions. For instance, the varying levels of development and governmental support across countries can significantly affect their capacity to implement the necessary measures for hydrogen production. Additionally, the calculation of saltwater transportation using pipelines can be improved by accounting for the diverse geography of each country. Furthermore, the current definition of water stress may be insufficient for a more rigorous and holistic study as it does not take into consideration the water quality issues such as desertification, pollution and eutrophication in different regions which can create a severe strain on potable water. This has profound impacts on the usability of the water for numerous purposes and can vary by country. Another limitation of this study is that the seasonality of water demand and supply is not considered in the calculations, which may also be insufficient for a more holistic study. Lastly, future technological developments that may influence water demand for hydrogen production were not considered.

Future Research

One important concept to consider in the future is fixed country-specific cultural characteristics, such as attitudes towards water and climate change, which can influence the outcomes of research grouped by country. Additionally, in order to make comparisons between countries more rigorous, future research should divide countries based on the population's access to potable water. Water stress due to desertification, population access to piped water, and other factors relating to water availability should be added for analysis during comparison. One idea for future research could be to explore the challenges associated with hydrogen production in the Middle East, which faces significant obstacles, including its reliance on fossil fuels, and identify strategies to overcome them.

Methods

Data Collection

The data for the estimated hydrogen production of each country by 2050 was based on multiple sources. To determine the water demand for hydrogen production, we utilized a value of 9L of water consumed per kg of hydrogen produced derived from reaction stoichiometry11. The data for the total available renewable water resource was sourced from the Food and Agricultural Organization of the United Nations; the total current water use for each country was also obtained from the same organization[24].

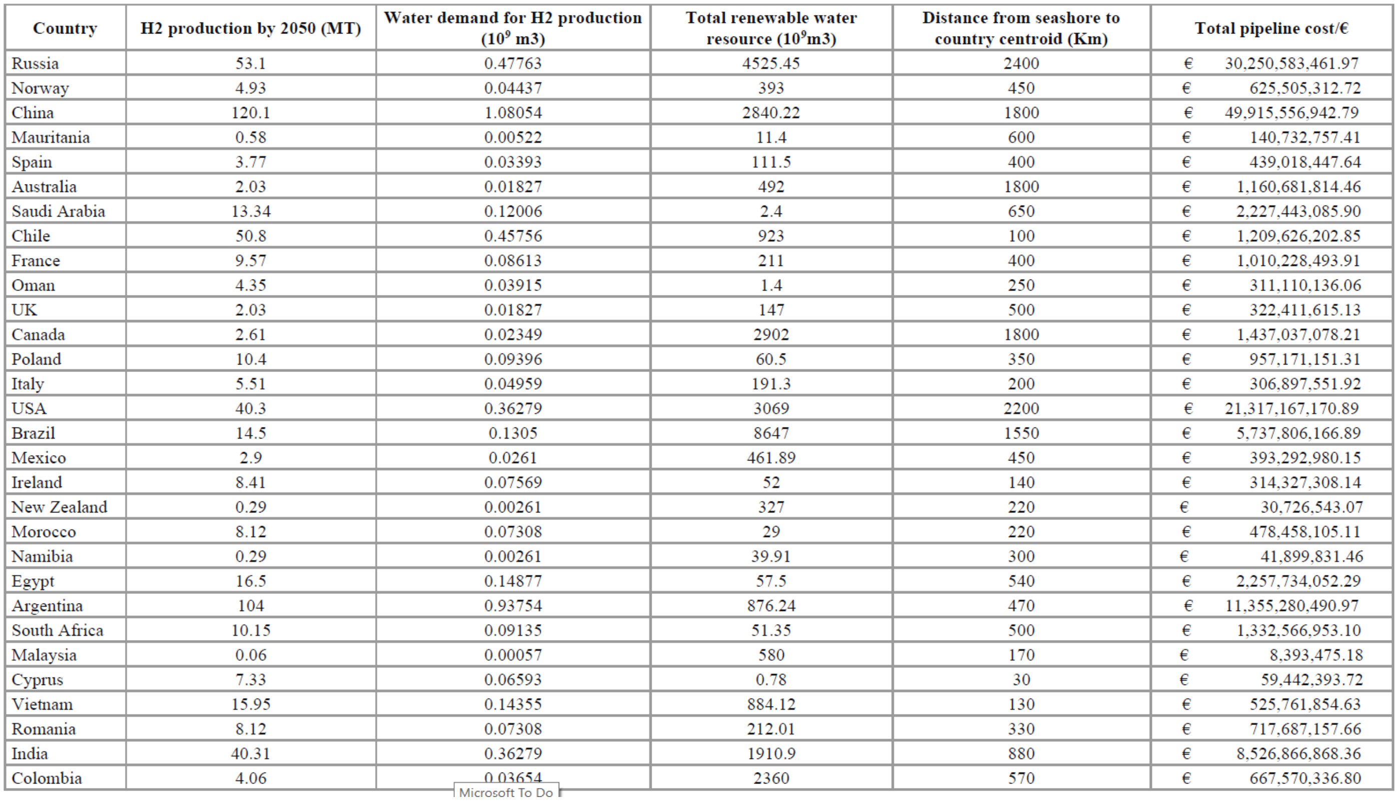
Investigation of viability of direct water electrolysis: In the investigation of water demand for hydrogen production, we used the data of 9L per kg of hydrogen obtained above. To calculate the water use for hydrogen production as a ratio of the total water supply, we divided the water demand by each country's combined renewable water supply, which includes both surface water and groundwater. We did not use total water per capita as a factor, as the hydrogen demand is also related to the population.

Next, we calculated each country's water stress by dividing its total current water use by its total renewable water resource. To categorize the countries by their level of water stress, we consulted data from Our World In Data and separated the countries into five categories based on their water stress levels (Table 1).

Water Stress Categories	Description
0-10	Low
10-20	Low to Medium
20-40	Medium to High
40-80	High
>80	Extremely High

Table 1 Water Stress Categories

Table 2. Key data and Results



Country	H2 production by 2050 (MT)	Water demand for H2 production (10^9 m3)	Total renewable water resource (10^9m3)	Distance from seashore to country centroid (Km)	Total pipeline cost/€
Russia	53.1	0.47763	4525.45	2400	€ 30,250,583,461.97
Norway	4.93	0.04437	393	450	€ 625,505,312.72
China	120.1	1.08054	2840.22	1800	€ 49,915,556,942.79
Mauritania	0.58	0.00522	11.4	600	€ 140,732,757.41
Spain	3.77	0.03393	111.5	400	€ 439,018,447.64
Australia	2.03	0.01827	492	1800	€ 1,160,681,814.46
Saudi Arabia	13.34	0.12006	2.4	650	€ 2,227,443,085.90
Chile	50.8	0.45756	923	100	€ 1,209,626,202.85
France	9.57	0.08613	211	400	€ 1,010,228,493.91
Oman	4.35	0.03915	1.4	250	€ 311,110,136.06
UK	2.03	0.01827	147	500	€ 322,411,615.13
Canada	2.61	0.02349	2902	1800	€ 1,437,037,078.21
Poland	10.4	0.09396	60.5	350	€ 957,171,151.31
Italy	5.51	0.04959	191.3	200	€ 306,897,551.92
USA	40.3	0.36279	3069	2200	€ 21,317,167,170.89
Brazil	14.5	0.1305	8647	1550	€ 5,737,806,166.89
Mexico	2.9	0.0261	461.89	450	€ 393,292,980.15
Ireland	8.41	0.07569	52	140	€ 314,327,308.14
New Zealand	0.29	0.00261	327	220	€ 30,726,543.07
Morocco	8.12	0.07308	29	220	€ 478,458,105.11
Namibia	0.29	0.00261	39.91	300	€ 41,899,831.46
Egypt	16.5	0.14877	57.5	540	€ 2,257,734,052.29
Argentina	104	0.93754	876.24	470	€ 11,355,280,490.97
South Africa	10.15	0.09135	51.35	500	€ 1,332,566,953.10
Malaysia	0.06	0.00057	580	170	€ 8,393,475.18
Cyprus	7.33	0.06593	0.78	30	€ 59,442,393.72
Vietnam	15.95	0.14355	884.12	130	€ 525,761,854.63
Romania	8.12	0.07308	212.01	330	€ 717,687,157.66
India	40.31	0.36279	1910.9	880	€ 8,526,866,868.36
Colombia	4.06	0.03654	2360	570	€ 667,570,336.80

Pipeline Calculations

To determine the cost of the pipeline required for water transportation, we first calculated the appropriate diameter needed to sustain the length and water demand using a formula depicted below:

$$\text{Cross sectional area (A)} = \frac{V}{u}$$

Derive to get:

$$\text{Diameter} = \sqrt{\frac{4 \cdot V}{\pi \cdot u}}$$

The flow rate was determined by dividing the total annual water demand of the country by the number of seconds in a year to obtain the water demand per second. We estimated the water velocity to be 1.5 m/s based on previous studies[25]; we obtained the water density of 1000 kg/m^3 from the Water Science School[26].

After calculating the diameter for each country, we determined the approximate distance that water needed to be transported by finding the distance from a country's shoreline to its center using digital maps (Figure 9). To obtain the construction cost for each country's length of pipeline, we used the formula $\text{Cost} = 0.0009 \cdot \text{dia}^2 + 0.2884 \cdot \text{dia}\,(\text{€/m of pipe})$, where dia is the diameter of the pipe in mm, and included a maintenance fee which was 2% of the construction cost to arrive at the total final cost of the pipeline for water transportation[27].

The key data and results for this study are presented in Table 2.

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