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Energy futures and green hydrogen production: Is Saudi Arabia trend?

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ABSTRACT

This paper explores the potential for hydrogen energy to become a future trend in Saudi Arabia energy industry. With the emergence of hydrogen as a promising clean energy source, there has been growing interest and investment in this area globally. This study investigated whether the country is likely to pursue this trend, given its current energy mix and policies. A study was conducted to provide an overview of the global trends and best practices in hydrogen energy adoption and investment. The outcomes of the analysis show that the country current energy mix has the potential to produce green hydrogen energy. The evaluation of its readiness and potential obstacles for hydrogen energy adoption has been drowned, and there are several challenges that need to be addressed. The study outcomes also conclude with policy implications and recommendations for the country energy industry.

1. Introduction

The transition towards cleaner and more sustainable energy sources is a global imperative in the face of climate change [1]. Hydrogen has emerged as a promising clean energy source that has the potential to reduce greenhouse gas emissions and mitigate climate change [2,3]. Saudi Arabia, a country known for its abundant oil and gas reserves, has not sufficient steps toward production and utilization hydrogen energy [4]. However, there is still uncertainty about the future of energy in the country and the role that hydrogen energy may play in shaping this future. Explore the potential for hydrogen energy to become a significant component of the country energy mix and contribute to its energy future. In addition, it examines the emergence of hydrogen economies and the potential for hydrogen to play a transformative role in the global energy landscape. Delves into the country current energy mix, energy policy, and the potential for hydrogen energy production. Evaluates Saudi Arabia readiness and potential obstacles for hydrogen energy adoption, including the challenges of infrastructure development and the economic feasibility of hydrogen energy.

1.1. Historical overview

Saudi Arabia has promoted low-carbon development during the last ten years via a range of local, regional, and global initiatives. The country 2030 vision seeks to make Saudi Arabi is energy system more productive. Its aims include encouraging fuel replacement (mostly from oil to gas) and putting energy-saving measures into action. The latter includes adjustments to the cost of household electricity and fuel. In 2020, the country took over the G20, an association of major industrialised and developing countries. Throughout its tenure, it played a leading role in advancing the circular carbon economy concept as a practical, international strategy for addressing runaway carbon dioxide emissions [5]. The G20 member nations energy ministers supported this approach, which is seen as a comprehensive approach to reducing emissions [6].

The conventional “take-make-dispose” approach serves as the foundation of the planned economy. The circular carbon economy, in comparison, emphasises energy and emissions transfers and adds recycling to advance toward sustainability. The four principles of the circular carbon economy are reduced, repurpose, recycle, and eliminate. The

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effectiveness of each pillar to reduce carbon emissions relies on the technologies, resources, and conditions in each nation, as well as supportive policies [7]. A technology-agnostic strategy, like circular decarbonization, is essential for lowering atmospheric carbon emissions at the lowest possible cost since no particular solution works for all countries.

Although the Saudi government unveiled its comprehensive plan in 2020, their involvement in hydrogen originally surfaced in 2010 when the department of industry and environment requested a national hydrogen study [8]. The study encouraged government funding in development and research and confirmed that growing greenhouse gas emissions were really the main driver behind studies into hydrogen energy. Although there is less publicly accessible material to support if and how this was advanced during the next 15 years by Saudi governments. The Saudi government has arguably been under increasing political pressure to address climate change both domestically and internationally [9], which has led to increased support for and investment in clean hydrogen.

A key facilitator in the circular carbon economy is hydrogen [10]. It can cross the four principles due to its adaptability in a wide range of situations and low-carbon manufacturing methods. On the supplier side, carbon dioxide emissions could be cut by changing the way hydrogen is made from grey to blue or green. Reducing greenhouse gas emissions is the obvious goal of clean hydrogen technology. According to the most recent studies, if emissions of greenhouse gases are not significantly reduced soon, global warming will reach 1.5° or more, causing catastrophic climatic change [11]. About 88% of global greenhouse gas emissions, according to evidence, are a result of using fossil fuels for transportation, heating, and power [12]. Superior alternative to fossil fuel usage is a global issue, and as global warming has become worse though future global warming projections have been more dire, the need to find a magic alternative fuel has increased.

It might take the place of hydrocarbons in the transportation and industrial sectors on the consumer side. Carbon dioxide may be recycled when carbon and hydrogen dioxide are combined to produce synthetic fuels like petroleum and artificial diesel. Improved oil recovery is one use for the collected carbon dioxide from the creation of hydrogen. As an option, carbon may be taken out and buried underground. The cyclical carbon country economic reduce, preserve, and recycle principles apply to both the green ammonium project in Neom and the demonstration shipment of blue ammonia to Japan. The country has abundant hydrocarbon resources, excellent potential for renewable energy, and energy industry know-how. So, it could become a key place to use and store carbon dioxide and hydrogen with low carbon emissions.

Each of the three major uses of fossil fuels, clean hydrogen serves as an alternative fuel source. In some circumstances, hydrogen may take the role of natural gas, which is currently utilized for heating, cooking, and in industrial applications [13]. As a compound with relatively simple electron extraction, hydrogen has the ability to contain chemical energy that may be utilized to store renewable energy and replace diesel and gasoline in transportation through fuel cell technology [14]. For these grounds, hydrogen is a possible energy source that requires no modification to daily life; instead, the use of hydrogen facilitates the continuance of current or comparable human activities. While the worldwide environmental crisis is one of the key forces driving the development of clean hydrogen, more evidence was needed, at particularly in the country, before government assistance could be attained.

The Saudi government has often come under fire for its inadequate climate policies and apathy on the issue. The Saudi government pledged support for the Climate Accord in 2016, even though there was evidence that indicated that the target of 28–30% reduction in emissions under 2010 levels by 2030 would be reached [15]. Assessments of the Saudi population reveal a growing public consensus about the need to take action to address climate change, and according to 2017 research from the environment and economic institute, king abdulaziz university by about 95% of Saudis said they preferred renewable energy [16]. The cost of renewable energy was falling in the country just at the time of the study, price of gas was increasing significantly, and many Saudis were becoming concerned about energy security [17].

Too far, Saudi Arabia and other countries have made considerable investments in the advancement and research of hydrogen technology. In addition to the multibillion-dollar developments in eastern Saudi Arabia, the government, industries, and entrepreneurs have committed more than 900 million dollars in hydrogen projects by 2020 [18]. The size of funded initiatives indicates that the country is moving away from investigation and demonstrations and toward larger-scale development [19,20]. Economic success and job creation are important promises made in communications promoting the hydrogen economy [21,22]. Although Australia has made large investments and has political will, there are still obstacles to the advancement of hydrogen. The hydrogen economy is said to be "very low" in situation since a supply of hydrogen cannot be ensured until there is market demand [23]. However, prospective producers are hesitant to make an investment until there is a market need. To solve this problem and create a thriving hydrogen economy, it will be important to find the most cost-effective, environmentally friendly, and socially acceptable way to make and extract large amounts of cheap, sustainable hydrogen. As of now, it is not clear which method of making hydrogen will be the most cost-effective, environmentally friendly, and socially acceptable [24].

The productive capacity of hydrogen energy has encouraged both government and private investment in hydrogen technology in addition to political pressure. The narrative of hydrogen has been affected economically by two primary factors: the declining cost of generating renewable energy as well as the realisation of the profitability the Saudi gas and oil export business enjoys. The production of clean hydrogen is currently considered to be an economically feasible option since wind and solar energy are now acknowledged as the least expensive new methods of power generation [25]. Saudi exports, estimated at $73.2 billion in 2021, represented more than 10% of Saudi entire export earnings [26]. However, because to the huge emissions generated by the sector, Saudi Arabia export of oil and gas is coming under more and more scrutiny [27]. The economic need to investigate natural gas transition possibilities has driven investment in the country hydrogen technologies development and research despite the fact that technical obstacles still exist [28].

1.2. Hydrogen demand

Several institutes provide a variety of hydrogen demand predictions due to the relative infancy of the hydrogen sector. In its environmental sustainability scenario, the International Energy Agency (IEA) hydrogen projects that worldwide hydrogen consumption will reach 35 EJ by 2050 [29]. In the case of a net-zero circumstance, the demand is predicted to be about 66 EJ [29]. According to research by the hydrogen council, in a multiple situation, hydrogen consumption will rise tenfold by 2050, hitting 78 EJ [30]. This is expected to satisfy 22% of the total demand for energy for the world diverse industries, including transit, commercial energy, power production, and building heating. By 2050, if we extrapolate and apply this supposition to the region anticipated energy requirements over a comparable time frame, it would take around 15 million tonnes of hydrogen annually to meet country target of getting 20% of its main energy needs from hydrogen [31].

1.3. Background of Saudi Arabia energy industry

Saudi Arabia is a country rich in natural resources, including oil and gas reserves that have been the backbone of its energy industry for decades [32]. The country is the largest producer and exporter of oil in the world, and its oil reserves are estimated to be the second-largest in the world. Saudi Arabia economy is heavily dependent on the oil and gas sector, accounting for about 50% of its GDP, 70% of government revenue, and 90% of its export earnings [33]. The country has been actively pursuing efforts to diversify its energy mix and reduce its dependence on oil exports. The government has announced ambitious plans to increase the share of renewable energy in the country energy mix, with a target of 50% renewable energy by 2030 [8,9]. The country has already made significant progress towards this goal, with the development of large-scale solar projects and wind farms [34]. Generally, the country energy industry has been traditionally focused on oil and gas production, but the country is now actively pursuing a more diversified and sustainable energy mix, including the potential for hydrogen energy to play a significant role in its energy future. Table 1 show some of the key developments and progress in the country energy industry from 2015 to 2022.

1.4. Saudi Arabia energy system

The country is known for its vast oil reserves and its position as a major player in the global energy industry. The country has historically relied heavily on oil exports as a source of revenue, with the oil and gas sector accounting for the majority of the country exports and government revenues [37].

1.4.1. Oil and gas

The country energy system has been dominated by oil and gas for decades, with the country possessing one of the largest reserves of oil in the world. The oil and gas sector has traditionally been the backbone of the country economy, with the majority of the country government revenues and exports coming from the sector [38]. Saudi Arabia oil and gas industry is largely state-owned, with the government controlling the majority of the country oil reserves and production. The country is a member of the Organization of the Petroleum Exporting Countries (OPEC), which controls a significant portion of the world oil supply [39,40]. The country oil and gas sector are heavily reliant on exports, with the majority of the country oil production being sold on the global market. The country has traditionally been a key supplier of oil to countries around the world, including the United States, Europe, and Asia.

According to data from the International Energy Agency (IEA), Saudi Arabia oil exports in 2020 were around 7.5 million barrels per day (bpd), which accounted for approximately 7.5% of global oil demand [41]. In terms of gas, the country exported around 0.3 trillion cubic feet (tcf) of natural gas in 2019, according to data from the U.S. Energy Information Administration (EIA) [17]. Fig. 1 show the oil and gas export for the years of 2015–2022.

It is worth noting that the country natural gas production and consumption are both increasing, and the country is investing in new infrastructure to support its domestic gas demand. As such, it may not continue to be a significant exporter of natural gas in the future.

Table 1
Progress in Saudi Arabia energy industry from 2015 to 2022 [35,36].

Year	Progress in Saudi Arabia Energy Industry
2015	Announced its Vision 2030 plan, which aimed to diversify the economy and reduce the country dependence on oil exports.
2016	Launched its National Renewable Energy Program, with the aim of developing 9.5 GW of renewable energy by 2023.
2017	Announced plans to invest $50 billion in renewable energy projects over the next decade.
2018	Announced plans to develop a 2.6 GW solar project, which would be one of the largest in the world.
2019	The country opened its first utility-scale wind farm, with a capacity of 400 MW.
2020	Launched its National Hydrogen Strategy, with the aim of becoming a major exporter of hydrogen by 2030.
2021	Established a Hydrogen Center of Excellence to promote the development of the renewable energy investigation.
2022	Announced plans to develop a $5 billion sustainable projects, which would be one of the largest in the world.

Generally, while the country is primarily known for its oil exports, it has also been a significant exporter of natural gas in the past. As the country looks to diversify its energy mix and reduce its dependence on fossil fuels, it may shift its focus towards new sources of energy, such as renewable energy and hydrogen.

1.4.2. Electrical energy

Saudi Arabia electricity production and consumption have been steadily increasing in recent years. In 2019, the country produced 336.5 TW-hours (TWh) of electricity and consumed 318.5 TWh, with a peak demand of 80.4 GW (GW) [43]. The majority of country electricity production comes from fossil fuels, with oil and gas accounting for over 90% of the country total electricity generation in 2019 [19]. Fig. 2 show the country electrical energy production and consumption for the years of 2015–2022.

The majority of country electrical energy production is from fossil fuels, with a small percentage from renewable sources as presented in Fig. 3. Despite these investments in renewable energy, fossil fuels are likely to remain the dominant source of electricity generation in the country for the foreseeable future. The country has significant reserves of oil and gas, and these resources will continue to play an important role in powering the economy.

To achieve this target, the country is investing heavily in expanding its renewable energy capacity, with a particular focus on solar and wind energy. As of 2021, the country had installed renewable energy capacity of 5.5 GW, with an additional 3.6 GW currently under construction. The largest renewable energy project in the country is the Noor Energy 1 solar project, which is expected to have a total capacity of 1.7 GW when completed [45].

1.4.3. Towards sustainability

Saudi Arabia has set ambitious targets to move towards sustainable energy production, with a particular focus on increasing the share of renewable energy sources in its electricity mix. The country Vision 2030 plan includes a goal to generate 50% of its electricity from renewable energy sources by 2030, which would significantly reduce the country dependence on fossil fuels and contribute to global efforts to combat climate change [46,47]. To achieve this goal, the country has launched several initiatives and projects aimed at increasing its renewable energy capacity. The country Renewable Energy Project Development Office (REPDO) has overseen the development of several large-scale renewable energy projects as described in Table 2.

In addition, country has also invested in research and development to support the growth of renewable energy technologies. The King Abdullah City for Atomic and Renewable Energy (K.A. CARE) has established partnerships with international organizations and research institutions to advance renewable energy research and development in the country [50]. Moreover, the Saudi government has introduced several policies and regulations to support the growth of renewable energy, including feed-in tariffs and net metering programs to encourage the deployment of small-scale renewable energy systems, as well as regulatory reforms to facilitate private sector investment in renewable energy projects.

1.5. The emergence of hydrogen energy as a potential future trend

The emergence of hydrogen energy as a potential future trend represents a significant shift in the global energy landscape [51]. Hydrogen, which is the most abundant element in the universe, has long been recognized as a potential energy carrier due to its high energy density and clean-burning properties. However, it is only in recent years that advances in technology, along with growing concerns about climate change and the need to transition towards cleaner and more sustainable energy sources, have brought hydrogen energy to the forefront of energy discussions [52]. One of the key advantages of hydrogen energy is that it produces zero greenhouse gas emissions when used as a fuel, making it a

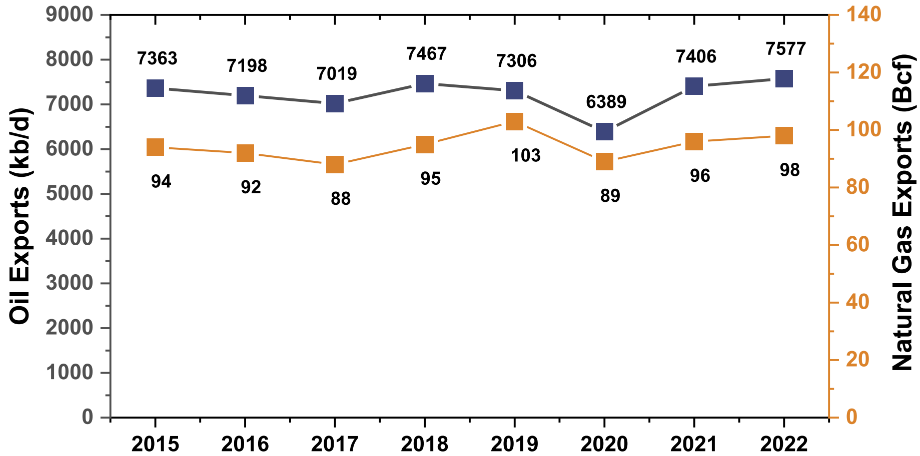

Fig. 1. Saudi Arabia oil and natural gas exports from 2015 to 2022 [14,42].

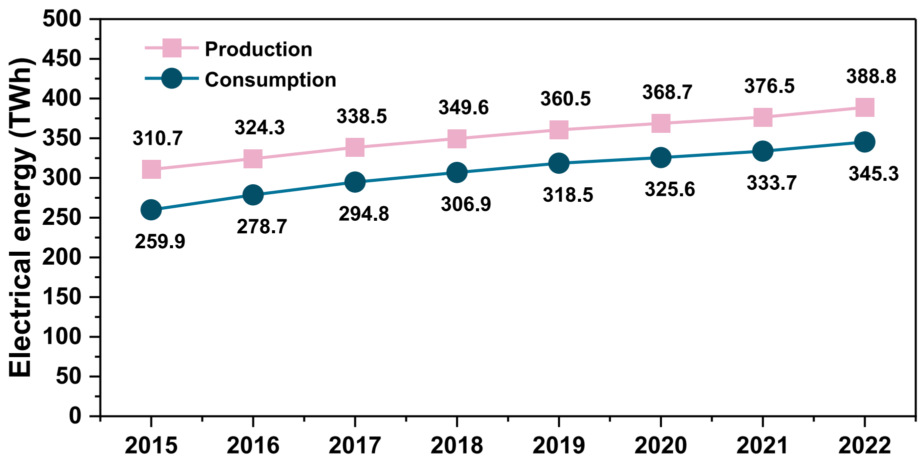

Fig. 2. Saudi Arabia electrical energy production and consumption from 2015 to 2022 [43,44].

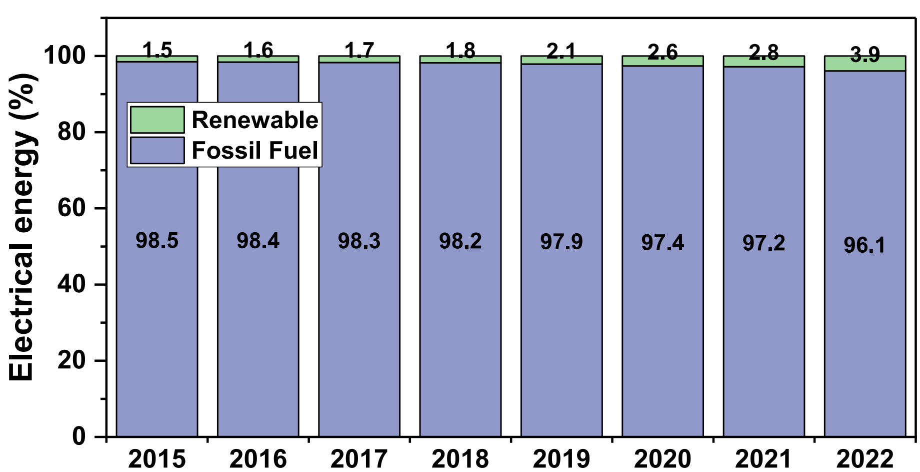

Fig. 3. Saudi Arabia electrical energy production percentage by form from 2015 to 2022 [43,44].

potentially important tool in the fight against climate change [53]. Additionally, hydrogen can be produced from a variety of sources, including water and renewable energy sources such as solar and wind power, making it a potentially versatile and sustainable energy source. There are currently two main methods of producing hydrogen: electrolysis, which involves splitting water molecules into hydrogen and oxygen using electricity, and steam methane reforming, which involves reacting natural gas with steam to produce hydrogen [54,55]. While both methods have their advantages and disadvantages, advances in technology are making hydrogen production more efficient and cost-effective.

Hydrogen energy can be used in a variety of applications, including transportation, electricity generation, and heating. In transportation, hydrogen fuel cell vehicles have the potential to provide a zero-emission

Table 2
Country projects towards sustainability by vision 2030 [48,49].

Project Name	Description
Neom	A $500 billion smart city project that will run entirely on renewable energy and will prioritize sustainable development.
Red sea tourism project	A sustainable tourism project that aims to protect the environment and promote conservation while developing the tourism industry.
Saudi green initiative	A comprehensive environmental initiative that aims to increase the country green cover, reduce carbon emissions, and promote sustainable practices.
Sustainable rural agricultural program	A program that aims to improve water efficiency, promote sustainable agriculture practices, and increase food security in rural areas.
Saudi energy efficiency program	A program that aims to reduce energy consumption in the country by promoting energy-efficient practices and technologies in residential, commercial, and industrial sectors.
Public transportation	Several public transportation projects are planned to reduce dependence on private cars, including the Riyadh Metro and Jeddah Metro, which are expected to be powered by renewable energy.

alternative to traditional internal combustion engines [56]. In electricity generation, hydrogen can be used in fuel cells to produce electricity, with the only byproduct being water. In heating, hydrogen can be used in place of natural gas in homes and businesses [57,58]. While the potential of hydrogen energy is significant, there are also challenges that must be overcome in order for it to become a viable and widespread energy source. One of the biggest challenges is the development of infrastructure to produce, transport, and store hydrogen [59]. Currently, there are limited infrastructure and distribution networks for hydrogen, which can make it expensive and challenging to transport and store. Additionally, the economic viability of hydrogen energy compared to other energy sources remains a question, as the cost of production and distribution is still relatively high.

Despite these challenges, the potential for hydrogen energy to play a transformative role in the global energy landscape cannot be ignored. Governments and industries around the world are investing in hydrogen energy research and development, with some countries already implementing policies and initiatives to promote its use. If the challenges of infrastructure development and economic viability can be overcome, hydrogen energy has the potential to become a significant part of the global energy mix, providing a cleaner and more sustainable energy source for the future.

1.6. *Study objective and novelty*

The study aims to explore the potential of green hydrogen production in Saudi Arabia and its implications for the country's energy future. The objective is to provide a comprehensive analysis of the unique context of Saudi Arabia as a major oil-producing nation with vast renewable energy resources and its potential for transitioning to a more sustainable energy future based on green hydrogen production.

The novelty of the paper lies in its focus on the specific circumstances of the Kingdom and its potential for green hydrogen production. The authors examine the current state of the energy industry in the Kingdom, its dependence on fossil fuels, and the growing global interest in clean energy alternatives. Moreover, the paper contributes to the discussion on the economic viability of green hydrogen production, taking into account the specific circumstances and potential revenue streams in the region. The analysis provides insights into the challenges and opportunities for policymakers and investors interested in the development of green hydrogen production in the country. Finally, the study offers a new perspective on the potential for green hydrogen production in Saudi Arabia, and its significance for the country's energy future and the global transition towards clean energy.

2. Protentional hydrogen form can produced in Saudi Arabia

The country several forms of hydrogen that can be produced as.

- **Grey hydrogen:** is the most common form of hydrogen produced globally, and it is produced through the steam methane reforming process, which involves the reaction of natural gas with steam to produce hydrogen and carbon dioxide [60,61]. However, this process is highly carbon-intensive and results in significant greenhouse gas emissions. Saudi Arabia is one of the largest producers and exporters of natural gas in the world, and it is also a major producer of grey hydrogen. The country has several natural gas processing plants, which use steam methane reforming technology to produce hydrogen. However, the production of grey hydrogen is not in line with the country vision of achieving sustainability and reducing greenhouse gas emissions.
- **Blue hydrogen:** The production of this form by another method that can be utilized in Saudi Arabia. This method is more sustainable and environmentally friendly than grey hydrogen production. In this process, carbon capture and storage (CCS) technologies are used to capture the carbon dioxide emissions produced during hydrogen production [62]. The captured carbon dioxide is then stored in underground geological formations, preventing it from being released into the atmosphere. Saudi Arabia has the potential to produce blue hydrogen as it has abundant natural gas resources, which can be used as a feedstock for hydrogen production. Additionally, the country has been investing in carbon capture and storage technologies in recent years, making it an ideal location for blue hydrogen production. Producing blue hydrogen can help the country to reduce its carbon emissions and meet its sustainability goals. The country has already taken steps towards achieving this, such as the establishment of the Saudi Carbon Capture and Utilization Company, which aims to capture carbon dioxide emissions and convert them into useful products [63]. In 2021, the company announced plans to build the world largest carbon capture and utilization plant, which will capture 1.5 million tons of carbon dioxide per year [64]. Generally, blue hydrogen production can provide a more sustainable and environmentally friendly option for hydrogen production in the country, while also supporting the country efforts towards achieving its sustainability goals.
- **Green hydrogen:** The production of this form is an emerging trend that has gained traction in recent years, particularly in countries with abundant renewable energy resources such as Saudi Arabia. Green hydrogen is produced by splitting water molecules into hydrogen and oxygen using electricity generated from renewable sources like solar, wind, or hydropower [65]. Unlike grey and blue hydrogen, green hydrogen production does not emit any carbon dioxide, making it a more environmentally friendly option. In Saudi Arabia, the potential for green hydrogen production is significant due to the country ample solar resources. The country has already made significant investments in renewable energy, and its ambitious renewable energy targets indicate a strong commitment to sustainable development. Additionally, the country has the advantage of having vast desert areas that can be used for the construction of large-scale solar farms. One of the significant advantages of green hydrogen production is its ability to store renewable energy [66]. This is particularly important in the country, where the country experiences peak energy demand during the hot summer months when the sun is most abundant. By producing green hydrogen during these times, excess solar energy can be stored and used later when demand is high. Despite the potential benefits, green hydrogen production in the country is still in its early stages, and significant investment and infrastructure development are needed to scale up production. However, with the country commitment to renewable energy and the potential for large-scale green hydrogen production, it is possible

that green hydrogen could become a key player in the country energy transition.

- **Turquoise hydrogen:** is a relatively new form of hydrogen that is produced using a combination of natural gas and renewable energy sources, such as wind or solar power [67,68]. The process involves using natural gas as a feedstock, but capturing and storing the resulting carbon dioxide emissions underground, preventing them from entering the atmosphere. The renewable energy sources are then used to power the process, reducing the overall carbon footprint of the production process. The country has significant potential for producing turquoise hydrogen due to its abundant natural gas reserves and its increasing investments in renewable energy. The country has set a target of producing 50% of its electricity from renewable sources by 2030, and is already home to one of the world largest solar power plants. The production of turquoise hydrogen can provide a significant opportunity for the country to diversify its energy mix and reduce its carbon footprint. In addition, the country can leverage its existing infrastructure for natural gas production and transportation to support the production of turquoise hydrogen. However, the production of turquoise hydrogen is currently more expensive than grey or blue hydrogen, and the technology is still in the early stages of development. As a result, there are several technical and economic challenges that need to be addressed before turquoise hydrogen can become a commercially viable option for the country. Nonetheless, with the country strong commitment to renewable energy and its abundance of natural gas resources, turquoise hydrogen has the potential to play a significant role in the country energy future.

It is worth noting that the most common forms of hydrogen production in the country are currently grey and blue hydrogen, due to the abundance of natural gas reserves in the country. However, there is a growing interest in green hydrogen as the costs of renewable energy continue to decrease, and the country aims to reduce its carbon emissions.

3. Overview of hydrogen energy and its potential as a future energy source

Hydrogen energy has been touted as a potential solution to the world energy problems due to its many advantages. Unlike fossil fuels, hydrogen produces no carbon emissions, making it a clean and sustainable source of energy [69]. Hydrogen can also be produced from a wide range of sources, including natural gas, biomass, and even water [70]. It is versatile and can be used in a range of applications, from powering cars to heating homes. Several studies have been conducted to explore the potential of hydrogen energy as a future energy source. The IEA found that hydrogen could play a crucial role in the energy transition to a more sustainable future [29]. The IEA report identified several key areas where hydrogen could be used, including transportation, power generation, and industrial processes. Another study conducted by the Hydrogen Council found that hydrogen could meet around 18% of the world energy needs by 2050, provided that significant investments are made in hydrogen technologies and infrastructure [30].

In terms of the current state of hydrogen energy, several countries, including Japan, South Korea, and Germany, have already made significant investments in hydrogen technologies and infrastructure [71]. In particular, Japan has been at the forefront of hydrogen energy development, with plans to build a “hydrogen society” by 2030 [72]. However, hydrogen energy has the potential to play a crucial role in the energy transition towards a more sustainable future. While there are still significant challenges to be addressed, including the cost-effectiveness of production methods and the development of infrastructure, several countries have already made significant investments in hydrogen technologies. Table 3. Show the large scale global green hydrogen projects.

Table 3
Global green hydrogen projects [73,74].

Project Name	Location	Capacity	Description
AquaVentus	Germany	10 GW	A project to develop offshore wind farms in the North Sea, with the excess electricity generated being used to produce green hydrogen through electrolysis. The project aims to have a capacity of 10 GW by 2035.
Green Hydrogen Hub	Australia	15 GW	A project that will use solar and wind energy to produce green hydrogen at a massive scale. It will be located in Western Australia Pilbara region, which has abundant renewable resources and established infrastructure for exporting commodities.
Gigastack	United Kingdom	3.6 GW	A project that aims to demonstrate the production of low-cost green hydrogen using offshore wind power. The project will utilize an electrolysis system that can be scaled up to 100 MW, with a goal of achieving a capacity of 3.6 GW by 2030.
NorthH_2	Netherlands, Germany	10 GW	A joint venture between gas infrastructure companies in the Netherlands and Germany to develop a green hydrogen value chain in the North Sea region. The project aims to build 10 GW of wind and solar capacity by 2040 to produce green hydrogen through electrolysis.
H_2 Green Steel	Sweden	5 GW	A project that aims to produce green hydrogen using renewable energy sources to power the production of fossil-free steel. The project will be located in the north of Sweden, where there is an abundant supply of renewable resources. The goal is to produce 5 million tons of steel annually by 2030.
Hyport Oostende	Belgium	50 MW	A project to build a green hydrogen production facility in the Port of Ostend using offshore wind power. The facility will have an initial capacity of 50 MW, with a goal of expanding to 400 MW by 2030. The hydrogen produced will be used in transportation, industry, and energy applications.
HyDeal Ambition	France, Spain	67 GW	A project to develop a green hydrogen value chain between France and Spain, utilizing renewable energy sources such as solar and wind power. The project aims to produce 3.6 million tons of green hydrogen annually by 2030, with a capacity of 67 GW.
AquaH_2	Norway	5 GW	A project that aims to produce green hydrogen using renewable energy sources such as offshore wind and hydropower. The hydrogen will be used in industries such as transportation, industry, and energy. The project aims to have a capacity of 5 GW by 2030.
Ørsted H2RES	Denmark	1.3 GW	A project that aims to develop an electrolysis facility powered by offshore wind, with a capacity of 1.3 GW. The project will be located in the North Sea, with the hydrogen produced being used in transportation and industry.

3.1. Global trends in hydrogen energy adoption and investment

Hydrogen energy is considered a key element in the world transition towards a more sustainable and low-carbon future. As such, there has been a surge in the adoption and investment in hydrogen energy projects globally. Here are some of the global trends in hydrogen energy adoption and investment.

- **Europe hydrogen strategy:** The European Union has set a goal to become carbon neutral by 2050, and has made hydrogen a priority in achieving this target. The EU hydrogen strategy includes investing in research and innovation, building a clean hydrogen economy, and supporting the development of a global hydrogen market [75].
- **Japan hydrogen roadmap:** Japan is aiming to become a "hydrogen society," with plans to use hydrogen as a primary energy source for power generation and transportation. The country has set a goal to produce 300,000 fuel cell vehicles and build 900 hydrogen refueling stations by 2030 [76].
- **South Korea hydrogen economy:** South Korea is investing heavily in the development of a hydrogen economy, with plans to increase the country hydrogen fuel cell vehicle fleet to 6.2 million by 2040. The government has also set a target to increase the country hydrogen production capacity to 5.26 million tons by 2040 [77].
- **Australia hydrogen exports:** Australia has abundant renewable energy resources and is well positioned to become a major exporter of green hydrogen. The country is investing in the development of large-scale hydrogen projects, such as the Asian Renewable Energy Hub, which aims to produce and export green hydrogen to countries in the Asia-Pacific region [78].
- **China hydrogen economy:** China is the world largest producer of hydrogen, and the government has set a goal to have one million fuel cell vehicles on the road by 2030 [79,80]. The country is also investing in the development of hydrogen fuel cell trucks, buses, and trains.
- **United States hydrogen initiatives:** The US Department of Energy has launched several initiatives to support the development of a hydrogen economy in the country. This includes funding for research and development, as well as partnerships with industry and academia to accelerate the deployment of hydrogen technologies [81].

The global trends in hydrogen energy adoption and investment show a strong commitment to a more sustainable and low-carbon future. With continued investment and innovation, hydrogen energy has the potential to play a significant role in meeting the world energy needs while reducing greenhouse gas emissions.

3.2. Saudi Arabia energy policy and its potential alignment with hydrogen energy

The country has recognized the need to diversify its energy mix and reduce its dependence on oil and gas. The Kingdom has been pursuing several initiatives aimed at enhancing energy efficiency, increasing renewable energy capacity, and exploring new sources of energy such as hydrogen. The country has set ambitious targets for the deployment of renewable energy and plans to increase the share of renewables in its energy mix to 50% by 2030.

In 2019, the Minister of Energy, Prince Abdulaziz bin Salman, announced the launch of the National Hydrogen Strategy, which aims to make the country a major player in the global hydrogen market. The strategy focuses on producing blue hydrogen from natural gas with carbon capture and storage (CCS) technology, as well as green hydrogen from renewable energy sources [82,83]. The plan aims to produce 1.2 million tons of green hydrogen and to supply 10% of the global demand for hydrogen by 2030. Furthermore, Saudi Arabia Public Investment Fund (SAPIF) has been investing in several energy projects globally, including a joint venture with Power and Air Products to develop a $5 billion green hydrogen-based ammonia production facility in NEOM, Saudi Arabia [84]. The facility will have a capacity of 1.2 GW and will produce 650 tons of green hydrogen per day.

The country energy policy required to shifted towards a more diversified and sustainable energy mix, with a focus on increasing renewable energy capacity and exploring new sources of energy such as hydrogen. The National Hydrogen Strategy and the country investments in global hydrogen projects required to commitment to becoming a major player in the hydrogen market and contributing to the global transition to a low-carbon economy.

4. Potential resources for green hydrogen production Saudi Arabia

There are several potential resources for green hydrogen production in the country such solar and wind.

Solar Energy: Saudi Arabia has one of the highest solar energy potentials in the world, and the government is committed to developing its renewable energy sector, particularly in solar energy, to reduce its dependence on fossil fuels. Green hydrogen, can be produced from renewable energy sources such as solar and wind, is a promising alternative to fossil fuels. The GIS map in Fig. 4, shows the potential solar irradiation in the country, which can be a key factor in determining the potential for solar energy generation.

As showed in Fig. 4, most parts of the country have a high level of solar irradiation, particularly in the central and northern regions of the country. Some cities in these regions with high solar irradiation levels that can be used for green hydrogen production include: Riyadh: 2200 kWh/m^2, Tabuk: 2500 kWh/m^2, Hail: 2500 kWh/m^2, Qurayyat: 2600 kWh/m^2, and Sakakah: 2700 kWh/m^2. These cities have the potential to produce significant amounts of solar energy for green hydrogen production, which can help the country reduce its carbon emissions and dependence on fossil fuels. The country has enormous potential for solar energy generation for green hydrogen production, and the government is actively promoting the development of large-scale solar projects for this purpose. With its abundant sunlight and vast desert areas, the country has the potential to become a major player in the global green hydrogen market.

Wind Energy: Saudi Arabia is also known for its significant wind

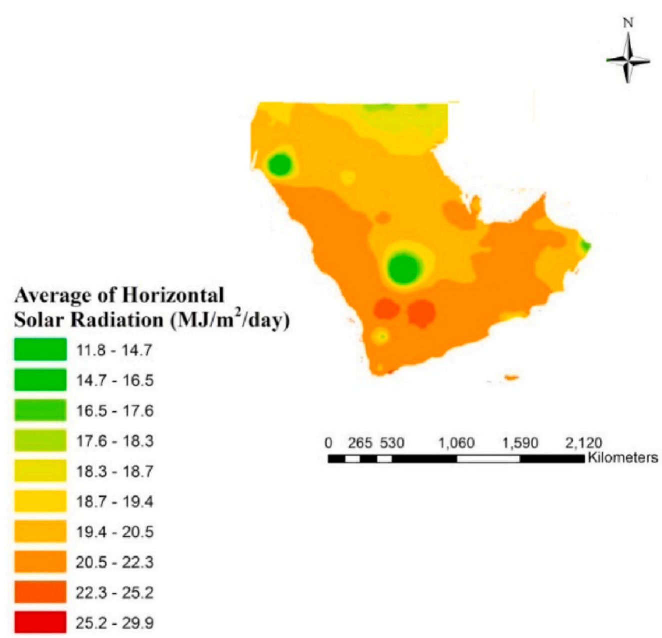

Fig. 4. Saudi Arabia potential solar irradiation (GIS map).

energy potential, particularly in the western and southwestern regions of the country. The GIS map in Fig. 5, shows the potential wind speed in the country, which can be a key factor in determining the potential for wind energy generation.

As presented in Fig. 5, the western and southwestern regions of the country have the highest wind power density, with some areas having wind power density greater than 500 W/m^2. Some cities in these regions with high wind power density levels that can be used for green hydrogen production include: Jeddah, Mecca, Taif, and Abha. These cities have the potential to produce significant amounts of wind energy for green hydrogen production.

The potential for wind energy in the country is significant, with the International Renewable Energy Agency (IRENA) estimating a potential of 50 GW of wind power. However, wind energy is not as developed in the country as solar energy, and the country Vision 2030 plan focuses more on developing its solar energy potential. While the country has significant potential for wind energy production for green hydrogen production, the focus is primarily on solar energy for renewable energy development in the country.

The country has several potential resources that can be utilized for green hydrogen production, and the country has already taken some steps towards utilizing these resources.

5. Current challenges of green hydrogen production in Saudi Arabia

In this section sum summarized the main challenges of green hydrogen production in the country as.

5.1. High cost of green hydrogen production: the main challenge for green hydrogen production in the country is the high cost of production, which can detail as

- **High capital costs:** green hydrogen production requires significant capital investments in infrastructure and technology. The cost of building renewable energy facilities, such as solar or wind farms, is still relatively high compared to fossil fuel-based energy systems [85]. As Saudi Arabia is still in the process of developing its renewable energy sector, it may require larger investments to establish the necessary infrastructure for green hydrogen production.
- **Limited economies of scale**: green hydrogen production in the country is currently at a small scale, which limits the economies of scale that can be achieved [86]. As production levels increase, the cost per unit of green hydrogen is expected to decrease, but this requires significant investments in infrastructure and technology.
- **High cost of electrolysis:** the main method of green hydrogen production is through water electrolysis, which is a relatively inefficient and costly process. Electrolysis requires large amounts of electricity to split water molecules into hydrogen and oxygen, which can be costly in regions where the cost of electricity is high. Saudi Arabia has a relatively high cost of electricity due to its reliance on fossil fuels for energy generation.
- **Limited access to water resources:** green hydrogen production requires large quantities of water for electrolysis, which can be a challenge in the country, where water resources are limited. Using seawater or brackish water can be a solution, but this adds to the cost of production [87].
- **Lack of demand and incentives:** there is currently limited demand for green hydrogen in the country, which makes it challenging to justify the high cost of production [88]. Most of the country industries still rely on fossil fuels, and there is a lack of incentives and regulations to promote the adoption of green hydrogen. As a result, there is a limited market for green hydrogen in Saudi Arabia, which can make it challenging to attract investors.

The high cost of green hydrogen production in the country is a significant challenge that requires significant investments in infrastructure, technology, and incentives to promote demand. As the country continues to develop its renewable energy sector and promote the adoption of green hydrogen, the cost of production is expected to decrease, making it a more viable option for various sectors.

*5.2. **Political and regulatory challenges:** another challenge for green hydrogen production in Saudi Arabia is political and regulatory barriers, which can detail as*

- **Fossil fuel dependency:** the country has a long history of relying on fossil fuels, and the oil and gas industry is a significant contributor to the country economy [89]. The government may be hesitant to invest in green hydrogen production, which could be seen as a threat to the country existing fossil fuel industry.
- **Lack of regulations:** The government has not yet developed a comprehensive regulatory framework for the production and distribution of green hydrogen [90,91]. This could create uncertainty for investors and limit the development of the industry.
- **Lack of infrastructure:** the infrastructure required for green hydrogen production and distribution is still in the early stages of development [92]. This includes the development of renewable energy sources, such as solar and wind power, as well as the construction of hydrogen production and distribution facilities.
- **Limited domestic market:** green hydrogen production may face challenges due to the limited domestic market for hydrogen. Most of the country energy consumption is focused on the oil and gas industry, and there is a limited market for green hydrogen in other sectors.
- **Limited international market:** The global market for green hydrogen is still in its early stages of development, and there is limited demand for green hydrogen on an international scale. This could limit the potential for exports of green hydrogen from Saudi Arabia.
- **Political instability:** Political instability in the region could create uncertainty for investors and limit the development of green hydrogen production in Saudi Arabia [93,94].

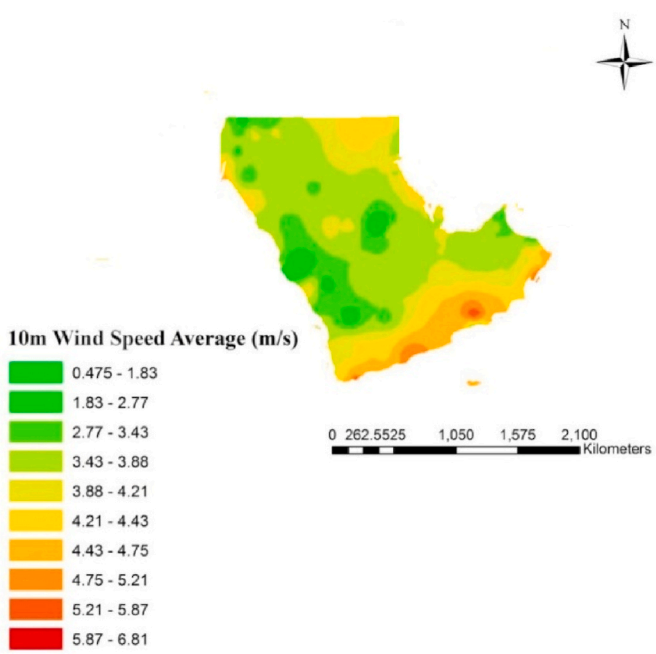

Fig. 5. Saudi Arabia potential wind speed (GIS map).

The political and regulatory barriers of green hydrogen production in country are significant challenges that must be addressed for the industry to develop. The government need to develop a comprehensive regulatory framework for green hydrogen production and distribution and invest in the necessary infrastructure to support the industry. Addressing these challenges will require a long-term commitment to the development of the green hydrogen industry, but the potential benefits of reducing the country reliance on fossil fuels and contributing to global decarbonization efforts make this a worthwhile endeavor.

*5.3. **Infrastructural limitations:** a another challenge for green hydrogen production in is the infrastructural limitations, specifically related to transportation, storage, and distribution as*

- **Limited hydrogen transportation infrastructure:** transporting hydrogen can be challenging due to its low energy density and the need for specialized equipment. In Saudi Arabia, there is currently a limited infrastructure for transporting hydrogen, which could limit the potential for exports or distribution to other parts of the country.
- **Limited hydrogen storage capacity:** hydrogen storage is an important component of the green hydrogen supply chain. However, hydrogen has a low energy density and requires specialized storage tanks and infrastructure. In Saudi Arabia, there is limited hydrogen storage capacity, which could limit the ability to store and distribute green hydrogen.
- **Limited distribution infrastructure:** the distribution of green hydrogen requires specialized infrastructure, including pipelines, compressors, and storage facilities. In Saudi Arabia, there is currently limited distribution infrastructure for green hydrogen, which could limit the ability to distribute it to other parts of the country or export it to other markets.
- **Dependence on fossil fuel infrastructure:** Saudi Arabia has an extensive network of fossil fuel infrastructure, including pipelines and storage facilities. While these infrastructure networks could potentially be adapted for the distribution of green hydrogen, there may be limitations in terms of compatibility and cost.
- **Dependence on import of components:** the construction of the infrastructure required for green hydrogen production, storage, and distribution requires specialized components and materials. In Saudi Arabia, the import of these components may be required, which could create additional costs and supply chain challenges.

The infrastructural limitations of green hydrogen production in Saudi Arabia related to transportation, storage, and distribution pose significant challenges that must be addressed for the industry to develop. Addressing these challenges will require significant investments in the development of specialized infrastructure and storage facilities. However, as the global demand for green hydrogen increases, the country strategic location and existing infrastructure could provide opportunities for exports and collaboration with other countries.

6. Roadmap toward green hydrogen production in Saudi Arabia

In this section we summarized a detailed roadmap for green hydrogen production as.

6.1. Establishing policy frameworks

- Develop a national hydrogen strategy that outlines the country goals for green hydrogen production, distribution, and utilization. The strategy should identify the key challenges and opportunities for green hydrogen in the country and outline a clear plan of action to achieve the country hydrogen-related goals.
- Create a supportive policy framework that incentivizes the production, distribution, and use of green hydrogen. This could include tax incentives, feed-in tariffs, regulatory frameworks, and other policy measures that promote the adoption of green hydrogen.
- Establish partnerships with other countries and international organizations to share best practices, lessons learned, and to promote the growth of the hydrogen economy.

6.2. Developing infrastructure

- Build green hydrogen production facilities using renewable energy sources such as solar and wind power. Saudi Arabia has abundant renewable energy resources, and these can be utilized to produce green hydrogen through electrolysis.
- Develop a network of pipelines for hydrogen transportation to connect production facilities with end-users such as industrial customers, transportation fleets, and fuel cell vehicles.
- Establish hydrogen refueling stations for fuel cell vehicles, which will help to promote the adoption of hydrogen-powered transportation in the country.

6.3. Building research and development capabilities

- Invest in academic research related to green hydrogen production, storage, transportation, and utilization. This could include funding for university research centers, research partnerships with international institutions, and investment in start-ups working on hydrogen-related technologies.
- Support the development of new technologies related to green hydrogen production and utilization, including research into hydrogen fuel cells, hydrogen storage, and hydrogen transport.
- Foster collaboration between research institutions, start-ups, and established companies in the hydrogen industry to drive innovation and accelerate the growth of the hydrogen economy.

6.4. Building capacity

- Develop a skilled workforce capable of designing, building, and operating green hydrogen infrastructure. This could include training programs, apprenticeships, and partnerships with technical colleges and universities.
- Establish a center of excellence for green hydrogen that brings together industry experts, academic researchers, and policy-makers to share knowledge and best practices.
- Encourage the participation of Saudi Arabian companies in the global hydrogen market by providing them with the necessary support and resources to compete effectively.

6.5. Encouraging collaboration

- Establish partnerships with other countries and international organizations to promote the growth of the hydrogen economy. This could include joint research projects, joint ventures, and partnerships with global companies working in the hydrogen sector.
- Foster collaboration between the private and public sectors to leverage the strengths of both sectors to promote the growth of the hydrogen economy.
- Develop a platform for knowledge sharing and collaboration that brings together key stakeholders in the hydrogen industry in Saudi Arabia.

6.6. Scaling up production

- Develop large-scale production facilities that can meet the growing demand for green hydrogen in Saudi Arabia and other markets.
- Invest in the development of export capabilities to supply green hydrogen to other countries that have set ambitious targets for decarbonization.

- Create new markets for green hydrogen by promoting its use in transportation, industry, and other sectors.

The roadmap for green hydrogen production in Saudi Arabia requires a comprehensive approach that includes the development of supportive policy frameworks, the establishment of hydrogen infrastructure, investment in research and development, building capacity, and promoting collaboration. With the right strategies in place, Saudi Arabia has the potential to become a leader in the global hydrogen economy.

7. Long-term map for green hydrogen production in Saudi Arabia

Saudi Arabia has the potential to become a major player in the global green hydrogen market, and a long-term map for green hydrogen production could help the country realize this potential. Fig. 6 show the detailed plan for green hydrogen production in the country.

Phase of 2023–2025: During this period, the focus should be on building the necessary infrastructure for green hydrogen production. This includes developing renewable energy sources such as wind and solar power, as well as establishing hydrogen production facilities. The government should incentivize private investment in renewable energy projects and establish partnerships with international companies with expertise in green hydrogen production.

Phase of 2025–2030: In this phase, the goal should be to increase the production of green hydrogen and make it more economically competitive with traditional hydrogen production. The government should continue to invest in renewable energy sources and encourage the private sector to do the same. The establishment of a domestic green hydrogen market should be a priority, with the aim of reducing dependence on traditional fossil fuels.

Phase of 2030–2035: By this point, green hydrogen production should be well-established in the country. The focus should shift to increasing the country exports of green hydrogen, particularly to Asia and Europe. The government should establish partnerships with countries that are seeking to transition to renewable energy sources, particularly those with a high demand for hydrogen.

Phase of 2035–2040: The final phase of the long-term map should focus on maximizing the potential of green hydrogen production in the country. This includes expanding the production of green hydrogen, increasing exports, and developing new applications for green hydrogen, such as in transportation and industry. The government should also invest in research and development to further reduce the cost of green hydrogen production and increase its efficiency.

The long-term map for green hydrogen production in the country should focus on building the necessary infrastructure, increasing production and competitiveness, expanding exports, and developing new applications. It will require a significant investment of time, resources, and expertise, but the potential benefits, both economic and environmental, are significant. With the right strategy and support, Saudi Arabia can become a leader in green hydrogen production and a key player in the transition to a more sustainable energy future.

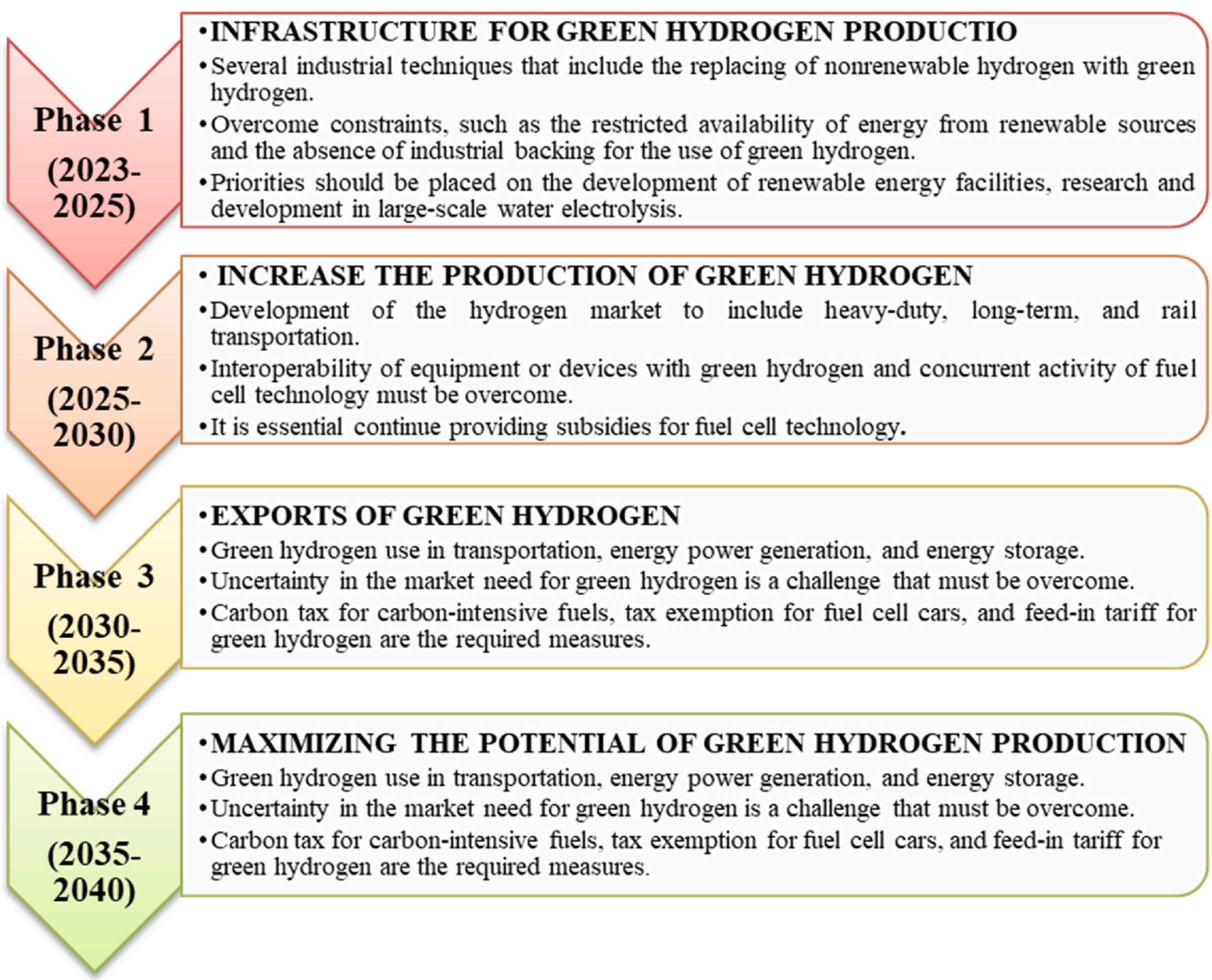

Fig. 6. Long-term map for green hydrogen production (2023–2040).

8. Conclusions

The country has the potential to become a major player in the global green hydrogen market, as it possesses abundant renewable resources such as solar and wind energy, and is currently one of the largest producers of conventional hydrogen. As the world continues to move towards decarbonization, green hydrogen is becoming increasingly important, as it is a sustainable and environmentally-friendly alternative to traditional hydrogen production methods. However, Saudi Arabia also faces significant challenges in its transition towards green hydrogen production, including high production costs, lack of infrastructure, and limited visibility of hydrogen utilization. The country will need to address these challenges by investing in research and development, incentivizing private investment in renewable energy projects, and establishing partnerships with international companies with expertise in green hydrogen production. In addition, a long-term roadmap for green hydrogen production in the country is crucial to guide the country transition towards a more sustainable energy future. The roadmap should focus on building the necessary infrastructure, increasing production and competitiveness, expanding exports, and developing new applications for green hydrogen. The roadmap will require a significant investment of time, resources, and expertise, but the potential benefits, both economic and environmental, are significant.

If Saudi Arabia successfully develops a sustainable green hydrogen industry, it will not only help the country reduce its dependence on traditional fossil fuels but also become a major player in the global green hydrogen market. This, in turn, will contribute to the country economic growth and diversification, as well as help mitigate the impact of climate change. While country faces significant challenges in its transition towards green hydrogen production, it also possesses significant potential for sustainable and environmentally-friendly energy production. It is clear that green hydrogen production is a trend that is here to stay, and as the world moves towards decarbonization, Saudi Arabia has an opportunity to become a leader in green hydrogen production and contribute to the global effort to mitigate climate change.

9. Future directions for green hydrogen production in Saudi Arabia

The country has a significant potential to become a leading player in the production and export of green hydrogen. To achieve this goal, the country needs to address the current limitations and implement a strategic plan that involves the following future directions.

- **Increase investment in renewable energy:** The cost of green hydrogen production is directly linked to the cost of renewable energy sources, particularly solar and wind. Therefore, to reduce the cost of green hydrogen production, Saudi Arabia must continue to invest in renewable energy infrastructure. This investment will not only help to reduce the cost of electricity but also ensure a sustainable and abundant supply of renewable energy for hydrogen production.
- **Develop a comprehensive hydrogen strategy:** Saudi the country Arabia needs to develop a comprehensive hydrogen strategy that outlines its vision for hydrogen and the steps it will take to achieve its goals. The strategy should include policies and regulations that support the development of the hydrogen industry, such as tax incentives and subsidies for green hydrogen production.
- **Foster international cooperation:** the country should work with international partners to develop a global hydrogen market. This cooperation could involve sharing expertise and resources, collaborating on research and development, and developing global standards for the production, transportation, and storage of hydrogen.
- **Build hydrogen infrastructure:** the country needs to invest in the infrastructure required to produce, transport, and store hydrogen. This includes the development of electrolyzers, pipelines, and storage facilities. The country should also consider developing a network of hydrogen refueling stations to support the use of hydrogen-powered vehicles.
- **Support research and development:** the country should continue to invest in research and development to improve the efficiency and reduce the cost of green hydrogen production. This could involve developing new materials for electrolyzers, improving the efficiency of renewable energy sources, and optimizing the process of hydrogen production.
- **Develop local demand for green hydrogen:** the country should look for ways to develop local demand for green hydrogen, such as using hydrogen in industrial processes or as a fuel for transportation. By developing local demand, Saudi Arabia can create a market for its green hydrogen and reduce its reliance on oil exports.
- **Promote education and awareness:** the country needs to promote education and awareness about the benefits of green hydrogen and the role it can **play** in achieving a sustainable future. This could involve launching public awareness campaigns and providing education and training for the workforce in the hydrogen industry.

The country has a significant potential to become a leading player in the production and export of green hydrogen. To achieve this goal, the country needs to address the current limitations and implement a strategic plan that includes increasing investment in renewable energy, developing a comprehensive hydrogen strategy, fostering international cooperation, building hydrogen infrastructure, supporting research and development, developing local demand for green hydrogen, and promoting education and awareness.

Declaration of competing interest

During submission you have checked the tick box saying that there is no conflict of interest. However the conflict of interest information is also provided in the text box.

Data availability

No data was used for the research described in the article.

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