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A Roadmap with Strategic Policy toward Green Hydrogen Production: The Case of Iraq

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Abstract: The study proposes a comprehensive framework to support the development of green hydrogen production, including the establishment of legal and regulatory frameworks, investment incentives, and public-private partnerships. Using official and public data from government agencies, the potential of renewable energy sources is studied, and some reasonable assumptions are made so that a full study and evaluation of hydrogen production in the country can be done. The information here proves beyond a doubt that renewable energy makes a big difference in making green hydrogen. This makes the country a leader in the field of making green hydrogen. Based on what it found, this research suggests a way for the country to have a green hydrogen economy by 2050. It is done in three steps: using green hydrogen as a fuel for industry, using green hydrogen in fuel cells, and selling hydrogen. On the other hand, the research found that making green hydrogen that can be used in Iraq and other developing countries is hard. There are technological, economic, and social problems, as well as policy consequences, that need to be solved.

Keywords: green hydrogen; roadmap; strategic policy; infrastructure; sustainable energy future

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1. Introduction

Energy consumption has significantly grown globally during the last several decades. The world energy situation was more significantly impacted than expected by global warming, wildfires, tremors, and the coronavirus pandemic that caused a serious acute respiratory crisis [1]. Scientists, researchers, and engineers have been working diligently in recent years to develop fresh approaches to producing renewable energy [2,3]. One way to meet rising energy needs without harming the environment is via the use of renewable energy. Increasing the utilisation of renewable energy sources, notably solar and wind power [4,5], represents the most effective strategy for decarbonizing the energy business. However, the broad use of renewable energy sources in the energy business for varied purposes faces a number of obstacles. Variability is one of the greatest obstacles to integrating renewable energy into the conventional energy infrastructure, especially for solar and wind energy [6].

Hydrogen is one of the most promising energy sources for the future [7]. It is an abundant element and can be produced from a variety of sources, making it a versatile energy carrier. The use of hydrogen as a fuel has been explored for many years, but recent developments in technology have made it more viable as a clean and sustainable energy source. Hydrogen has a number of advantages over other energy sources. It is a clean fuel, producing only water and heat when it is burned, and it does not release greenhouse gases [8]. This makes it an attractive option for countries looking to reduce their carbon emissions and meet climate targets. Additionally, hydrogen can be produced using renewable energy sources, such as wind or solar power, through a process called electrolysis. This is known as green hydrogen, and it has the potential to provide truly carbon-free energy.

Hydrogen can also be used in a variety of applications. It can power vehicles, heat buildings, and provide energy for industrial processes [9]. It can be stored and transported easily, making it a flexible energy carrier. It can be compressed and stored in tanks or transported via pipelines, and it can also be converted back into electricity using fuel cells, providing a clean and reliable source of energy.

The integration of solar and wind energy systems with water electrolysers for the production of hydrogen from renewable sources is a viable option despite the presence of a number of technological obstacles to the process of capturing green hydrogen [10]. This would offset their intermittent nature and contribute to the reduction of emissions from energy for many uses. Hydrogen derived from renewable sources may be used for a variety of sustainable energy applications, including industrial and transportation operations, such as steel manufacturing and petroleum refining, as well as the creation of various chemicals, such as nitrogen or methane. Recent books and articles have talked about many different ways hydrogen can be used. A cursory research study reveals the significance of several hydrogen production techniques, such as photoelectrolysis, electrolysis, thermo-chemical water electrolysis, and renewable technologies [11]. The transformation of electricity into hydrogen has a lower technological efficiency. This technique will become much more practical as the price of electrolysers and energy storage devices decreases. Particularly, more efficient electrolyzer systems should be researched and implemented [12].

Hydrogen production, distribution, and uses have been covered before; however, the quickly changing predictions and energy marketization as a result of technical advancement, economic analysis, and pertinent legislation need a second examination. Consequently, this article analyses and documents several areas of green production of hydrogen utilisation, such as production methods, storage, transportation, uses, sustainability, and sanitation, depending on the energy sources and feedstocks that may aid Iraq future development. Finally, the difficulties of using green hydrogen are discussed, as well as the level of technological and economic preparedness for the country.

1.1. Motivation

Despite the fact that renewable hydrogen is an effective means of reducing carbon emissions, high energy prices and capital costs are significant impediments to the construction of electrolysis plants. Whereas a variety of studies have analysed the economic feasibility of specific hydrogen production and storage facilities in the Middle East, few have studied the potential costs of hydrogen production technologies in Iraq. To the best of our knowledge, no study has been conducted on the technical and economic uncertainties that may affect the sustainability of green hydrogen production in petroleum-producing parts of the country. In addition, there is a lack of future studies that provide a deeper knowledge of the crucial role hydrogen would have in the development potential of oil and gas areas in transition. Therefore, the purpose of this study is to provide academics and decision-makers with timely and scientifically sound information on green hydrogen production in Iraq and the Middle East.

In light of this, the objectives of this research are threefold:

- to characterise the Iraqi power system and the local renewable energy resources that can be used to produce hydrogen through electrolysis of water.
- to conduct a statistical analysis of the technical and economic feasibility of producing hydrogen from potential sustainable energy.
- to explore the elements that may impede the Iraqi green hydrogen strategy implementation.

The absence of contemporary research in the country restricts the scope for a political discussion on the technical solutions available for the production of sustainable energy, despite the growing number of studies examining the role of green energy conversion in the future. As a consequence, the current research aims to fill this void and add to the body of knowledge on all fronts.

1.2. Novelty

The paper provides a novel approach to the issue of green hydrogen production in Iraq by presenting an in-depth analysis of the current challenges and a comprehensive roadmap to achieve a successful green hydrogen production industry in the country. It also discusses the potential of green hydrogen production in the country, particularly in terms of its potential applications and benefits. Furthermore, the paper presents a detailed overview of the current technological advancements and the potential for green hydrogen production in the region. The paper outlines the necessary steps to be taken in order to develop a successful green hydrogen production industry in the country, including the need for increased investment in relevant technologies, the development of suitable policies and regulations, and the need for better coordination among stakeholders.

2. Overview of Hydrogen Production Techniques

Approximately 87 million tonnes of non-renewable and renewable sources are used to manufacture hydrogen annually [13,14]. As of 2020, however, around 94% of hydrogen was generated from non-renewable sources, mostly steam reforming of oil and gas, which released approximately 855 million tonnes of carbon dioxide annually. The remaining 6% of hydrogen was created using renewable energy sources such as hydrogen production [15]. The usage of hydrogen production technology is shown in Figure 1.

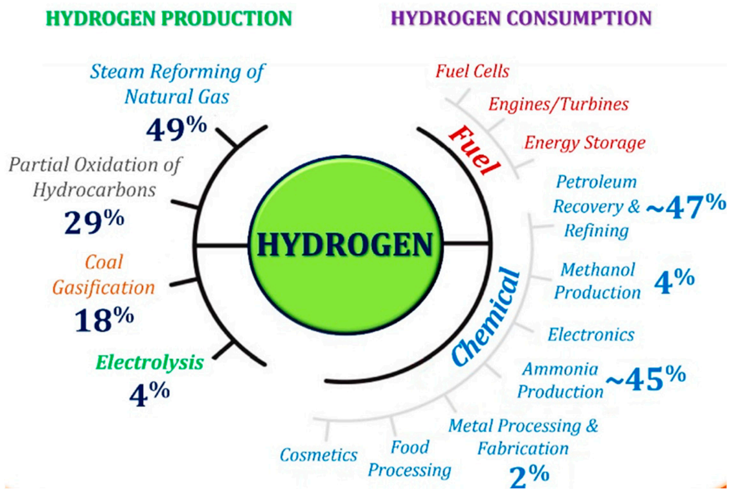

Figure 1. The approximate percentage of hydrogen production techniques and applications [16].

As shown in Table 1, hydrogen is subdivided into several colours, including green, blue, grey, brown, and black, based on its manufacturing method, energy source, and environmental impact [17]. Using electrolysis and thermo-chemical processes, it is possible to produce clean hydrogen from renewable energy sources. These approaches are either undergoing active studies and development or have been commercialised. These technologies, though, demand energy, water, and chemicals. In contrast, biohydrogen may be produced utilising biological treatment techniques and wastewater containing organic compounds. This method permits the treatment or reclamation of wastewater while simultaneously creating hydrogen [18]. Whenever their ecological implications are examined, current hydrogen manufacturing processes cannot be characterised as clean [19]. However, while implementing clean hydrogen production methods, it is also necessary to assess the energy source and the impact of materials used in manufacture [20]. Utilizing electrolysis-produced hydrogen in all consuming sectors might lessen environmental impacts. Moreover, the clean hydrogen production technologies are far more ecologically favourable than conventional methods.

Table 1. Hydrogen types, production technologies, emission, and approximated cost [17,20].

Hydrogen Type	Used Process	Production Technology	Products	CO_2 Emission Level	Hydrogen Cost ($/kg)
Green	Electrolysis	Water	$H_2 + O_2$	Very low	2.5–5
Blue	Reforming + carbon capture	Natural gas	$H_2 + CO_2$	Low	1.5–3
Gray	Reforming	Natural gas	$H_2 + CO_2$	Medium	1–2.2
Brown	Gasification	Lignite	$H_2 + CO_2$	High	1–2.5
Black	Gasification	Black coal	$H_2 + CO_2$	High	1–2.5

Green hydrogen plays an important part in the emissions reduction, which considered a viable fuel for sustainable future progress and energy transitions owing to the fact that it can be produced by water and sources of renewable electricity through the electrolysis process, with no emission of greenhouse gases. To prevent global warming and achieve net-zero problems on a worldwide scale, green hydrogen has been progressively advocated. In addition, the worldwide market for green hydrogen and its uses is anticipated to grow significantly in the coming years. Fortunately, the production of green hydrogen from renewable energy sources such as wind and solar is currently happening on a worldwide scale [21].

3. Iraqi Energy System

The Iraqi energy system has heavily relied on these resources for decades, making the energy sector a vital component of the country's economy. In this context, this section provided an overview of Iraqi energy system, focusing on its oil and gas industry, electricity generation, and efforts towards sustainable energy.

3.1. Oil and Gas

Iraq is a significant player in the global energy sector. Importantly, the volatile nature of global oil prices has had a significant impact on the country budgetary income and capacity to advance its long-term economic growth ambitions. In the previous two decades, the country had to devote a substantial amount of time and money to waging conflicts. Consequently, there have been substantial changes in the global energy markets. In the 2013 study, the increase of US oil extraction was identified as the "oil production trend of significance to Iraq".

Since 2012, significant progress has been achieved in a variety of fields. In the petroleum industry, output has climbed by half to about 5 million barrels per day by the year of 2017, driving country to the position of third-largest crude oil exporter in the world. However, improvement has been uneven across energy sectors. During 2013 and 2019, electricity output increased by about 90%, yet the difference between supply and peak demand is now greater than it was in 2021 [22–25]. The fact that the country power supply is not enough to meet peak demand, especially in the summer, is a big problem for everyone.

3.2. Electrical Energy

The Iraqi energy sector confronts tremendous challenges. The majority of families continue to experience power outages on a daily basis due to the fact that the increased producing capacity has been outpaced by the rising demand for energy, driven mostly by the high need for air conditioning during the summer months. In spite of a one-third increase in the available supply, the gap between peak energy demand and maximum grid supply has worsened during the last seven years as showed in Figure 2. As a result of financial constraints brought on by a time of low oil prices, infrastructure projects, especially in the transmission network, have slipped behind what is necessary. In the meantime, collecting tariffs has not been enough to support the financial plan in places where it is done. This results in a negative cycle in which fewer revenues lead to decreased capital expenditures, which in turn restrict availability and profits.

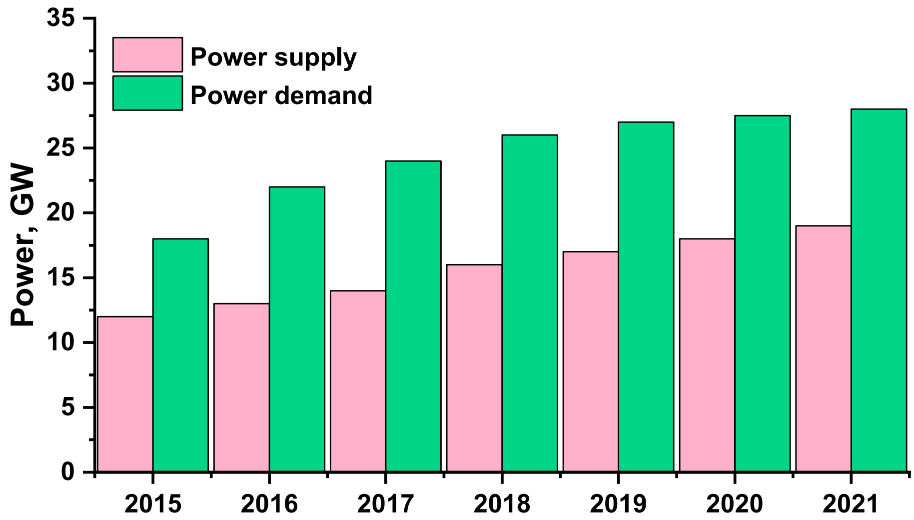

Figure 2. Power demand and supply 2015–2021 [26,27].

Small generators are essential for boosting grid capacity and easing some of the most severe shortages during the busiest summer months. The overall output of all diesel generators in 2018 was 6 GW [27]. Important for the individual to paying customers are supplied by the about two-thirds of the total that are privately funded and designated to as community producers.

3.3. Towards Sustainable Energy

There are many options for the future of Iraq electrical supply. The most economical, reliable, and sustainable route calls for reducing network losses by at least 55%, boosting regional interconnectivity, using captured gas in effective energy plants, and increasing the percentage of renewable energy sources in the mix of energy sources. Long-term solutions to the electricity sector problems are readily accessible. Distribution and transmission networks should indeed be completely modernised and expanded as part of comprehensive programmes to handle present difficulties, take changing demands into account, and establish the foundation for the future.

While meeting expanding demand will continue to be a problem, implementing proactive measures now might put country power sector on a new course that would benefit consumers, the administration, and the country industry as a whole. The expected rise in power usage from 81 TWh in 2025 to around 160 TWh in 2030. The amount of power produced domestically, imported, and locally would need to quadruple for a total supply of more than 260 TWh if the existing structure of the electrical supply were maintained as shown in Figure 3. If technical losses remained at 45%, more than 95 TWh, more than the total amount of power used today would be lost before it reached customers [28]. With more petroleum generated, oil product demand would increase from around 300 thousand barrels/day in 2025 to over 500 thousand barrels/day [28]. The amount of gas used for electricity production would rise to 36 billion cubic metres by 2030. Even maintaining the current structure of the power supply should not be taken for granted, since doing so would require more than three times the amount of money invested in the power industry in the past.

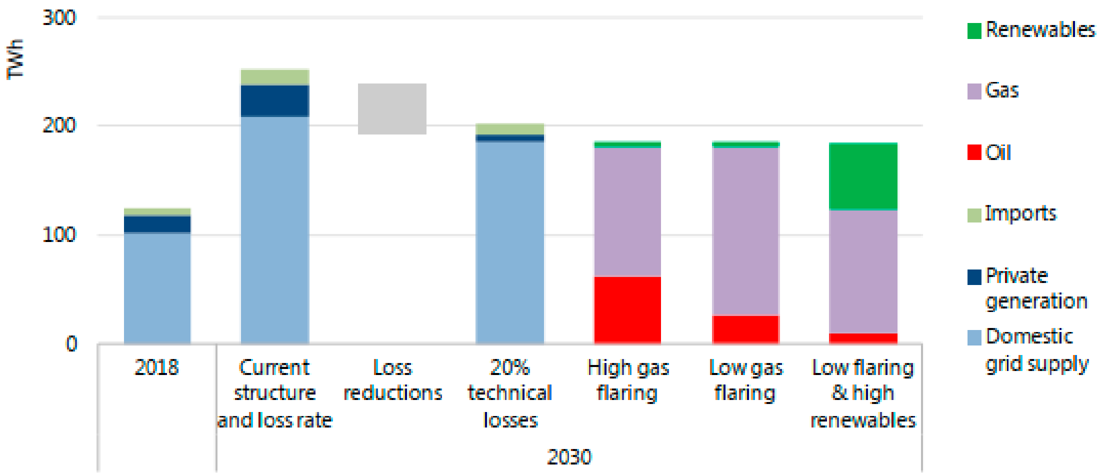

Figure 3. Steps towards supply sustainable electricity system in Iraq by 2030 [28].

4. Forms of Hydrogen That Can Produce in Iraq

The country has the potential to produce various forms of hydrogen due to its abundant natural resources, including renewable energy sources and natural gas reserves. Here are some forms of hydrogen that can be produced in the country:

- **Green Hydrogen:** Iraq has a significant potential for producing green hydrogen, which is produced through the process of electrolysis using renewable energy sources such as solar or wind power to split water molecules into hydrogen and oxygen. The country has vast solar energy resources, and its windy regions make it an ideal location for the development of wind energy projects. The production of green hydrogen in the country could contribute to the country's efforts to reduce its carbon footprint and transition to a low-carbon economy [29].
- **Blue Hydrogen:** The country has significant natural gas reserves, and producing blue hydrogen through the process of steam methane reforming (SMR) is another option. This process involves using natural gas to produce hydrogen, with the carbon dioxide emissions being captured and stored underground. The captured carbon dioxide can be used for enhanced oil recovery or other industrial processes [30]. The production of blue hydrogen could provide an alternative to traditional fossil fuels and contribute to the country's energy security.
- **Grey Hydrogen:** Grey hydrogen can be produced from natural gas through the process of steam methane reforming, which is a mature technology that is widely used globally. Iraq is one of the largest producers of natural gas in the Middle East, with proven reserves of over 3.5 trillion cubic meters [31]. The majority of the country natural gas is associated with oil production, and much of it is currently flared or reinjected back into oil reservoirs due to a lack of infrastructure and processing facilities. However, the authorities taking steps to develop its natural gas infrastructure, including the construction of new processing plants and pipelines [32]. This could pave the way for increased grey hydrogen production in the country, particularly in the petrochemical and fertilizer industries, which are major consumers of hydrogen. Moreover, grey hydrogen production could provide a source of revenue for the country, as it could potentially be exported to other countries in the region or globally. This could help to diversify the country economy and reduce its dependence on oil exports.
- **Turquoise hydrogen:** this is a relatively new form of hydrogen that is produced from natural gas, with the carbon dioxide emissions being captured and used for other purposes such as enhanced oil recovery [33]. This process is currently being researched and developed and could become a viable option in the future, especially for countries like Iraq that have significant natural gas reserves. The country has some of the largest natural gas reserves in the world, and producing turquoise hydrogen could be a promising option for the country [34,35]. By capturing and utilizing the carbon

dioxide emissions, turquoise hydrogen production could help reduce greenhouse gas emissions and contribute to the country's efforts to combat climate change. Turquoise hydrogen production could be a promising option for the country, given the country's large natural gas reserves and significant potential for enhanced oil recovery. By capturing and utilizing the carbon dioxide emissions, turquoise hydrogen production could help reduce greenhouse gas emissions and contribute to the country's efforts to combat climate change.

The country has the potential to produce various forms of hydrogen, with green and blue hydrogen being the most promising options. The production of green hydrogen in Iraq could contribute to the country's efforts to reduce its carbon footprint and transition to a low-carbon economy, while the production of blue hydrogen could provide an alternative to traditional fossil fuels and contribute to the country's energy security.

5. Recommended Resources for Green Hydrogen Production

Green hydrogen production in Iraq has the potential to play a critical role in the transition to sustainable energy systems and reducing the country's reliance on fossil fuels. Several renewable energy sources can be used to produce green hydrogen, including solar, water, wind, hydroelectricity, and biomass.

5.1. Hydrogen Production by Solar Energy

Using an empirical hourly solar radiation for the period of 19 years, Hassan et al. [36] assessed the prospective solar radiation for Iraqi provinces as presented in Figure 4. Additionally, methods for estimating the optimal tilt angle adjustments have been described together with the monthly and annual optimum tilt angle adjustments for receiving the greatest solar irradiation. The annual sunlight intensity varied from 3.89 to 4.7 kWh/m^2/day. Iraq is among the nations that can create power utilising solar energy since it has good solar resources. Similar to other countries, Iraq has recognised the value of solar energy. According to projections, country will possess some of the most abundant sources of renewable energy. The typical solar irradiation in Iraq is comparable to that in North Africa, despite the fact that the best solar radiation in the Middle East may be found towards the southeast, such as in Saudi Arabia.

Solar is the most extensively employed source of renewable energy for producing green hydrogen [37]. According to the Iraqi ministry of energy, may attain its 20–40% renewable energy penetration by 2030 by boosting solar energy from variable sources [38]. In tandem with the country efforts to minimise its reliance on oil and natural gas, the investment costs associated with solar and technology continue to decline, making the economic installation of these plentiful resources more feasible [39]. Since the intermittent nature of renewable energy supplies, their integration into the power system may create power fluctuations; however, these impacts can be mitigated by "trying to smooth" using energy storage technologies [40]. Batteries, pumping hydroelectric, electric cars, and green hydrogen, which has the benefit of being a non-carbon energy transporter that may be utilised for long-term or seasonal storage [41] are among the alternative storage solutions. The combination of solar and other renewable systems with an electrolyzer has strong economic potential owing to the benefits of high effectiveness, relative affordability, and high efficiency, which reduce the cost of production of green hydrogen [42,43].

5.2. Hydrogen Production by Wind Energy

According to the yearly average wind speed, Iraq may be classified into three regions. The first region, which makes up 47% of the country, has yearly wind speeds between 2.5 and 5.5 m/s. The wind between 3.2 m/s and 4.8 m/s in the second region, which makes up 3.1%. The third region, which makes up 7.0% of the country, has a wind speed that is comparatively high at around 5.5 m/s [44]. In Iraq, summertime winds are often stronger than wintertime winds. The projected densities given above are based on the yearly mean of recorded wind speeds over a period of 10 years [45]. Figure 5 shows the results of collection of all the recorded and published wind statistics for the years 2010 to 2020 from different sources for four main cities.

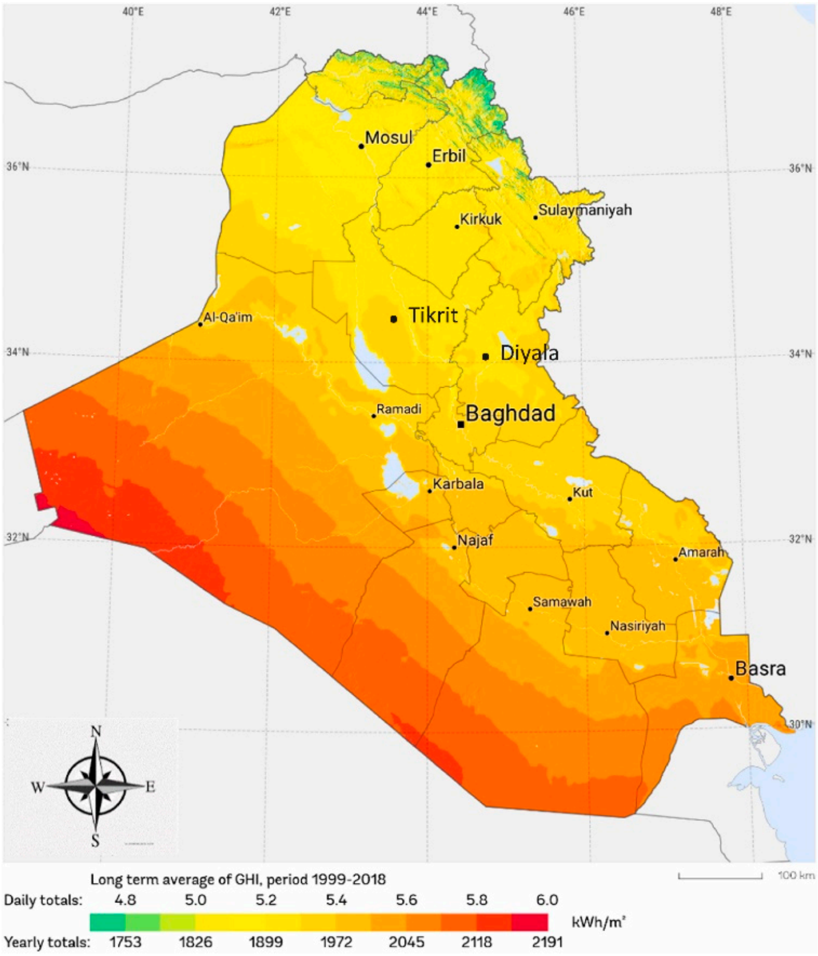

Figure 4. Potential solar irradaince in Iraqi territories [36].

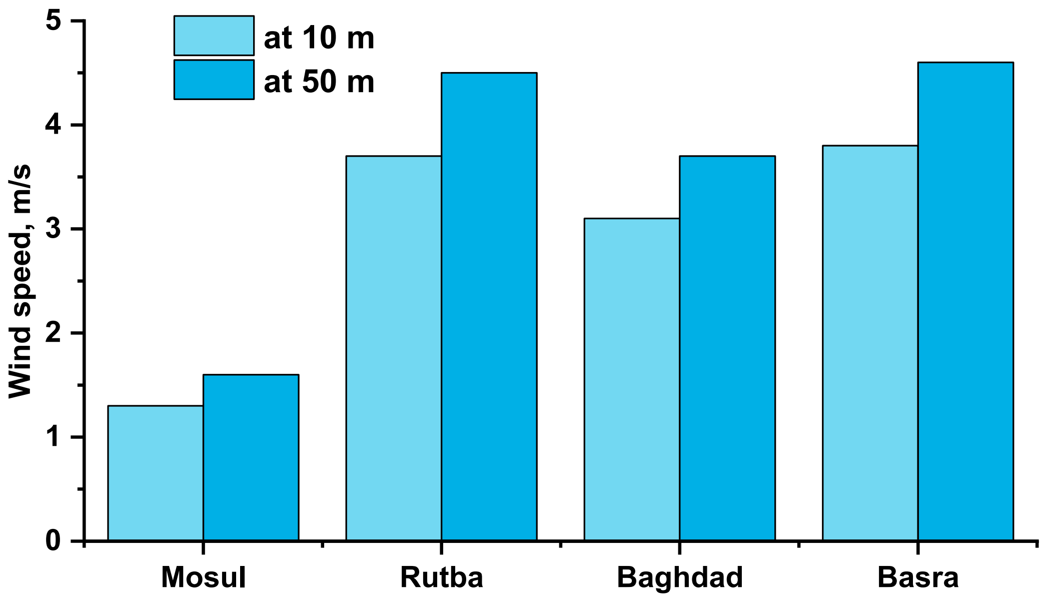

Figure 5. Annual wind speed average for four main cities in Iraq (North: Mosul; West: Rutba; East: Baghdad; South: Basra) [46].

Wind power is the most extensively employed renewable source of energy for green hydrogen production [47]. By encouraging variable renewable resources, the Iraqi electrical ministry may attain an approximately 15% penetration of renewable energy by 2030. In tandem with the administration efforts to minimise its reliance on fossil fuels, the infrastructure costs of wind turbines have gradually declined, making the socioeconomic installation of these plentiful resources more feasible [48,49]. Due to the intermittent nature of wind energy resources, their incorporation into the electricity system might create voltage fluctuations; however, these impacts can be mitigated by the use of energy storage technologies [50]. The combination of wind and other sources of renewable electricity has significant economic potential owing to the efficiency benefits.

5.3. Hydrogen Production by Hydro Energy

Currently, hydroelectric power accounts for around 13% of the installed capacity for energy production in Iraq. The installed capacity of hydroelectric plants reached 1955 MW at the end of 2018, but the produced electricity was only 912 MW [51]. Current hydropower facilities fall into two primary categories, the first group consists of hydroelectric facilities with lakes and reservoirs, whereas the second group consists of those with available storage bombardments. These are shown in Figure 6.

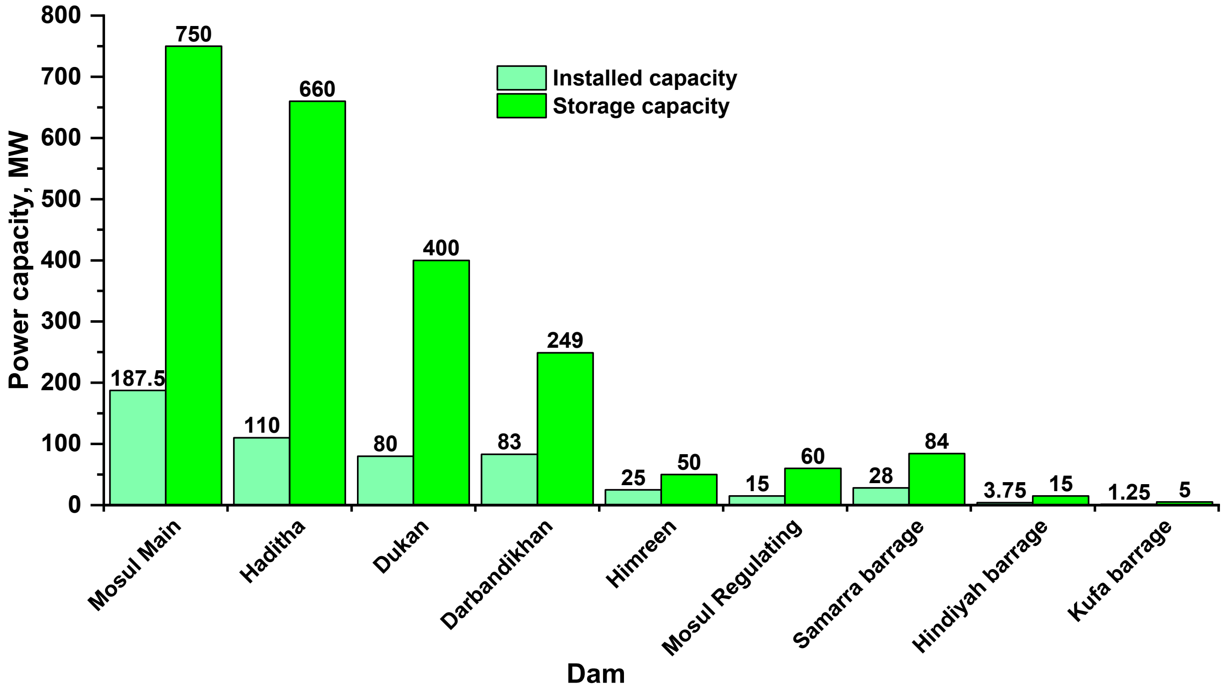

Figure 6. Current hydropower dams in Iraq [52].

By 2035, the country intends to expand hydropower use by up to 15 TWh. Figure 7 presents the development and planning with their capacity and locations.

Hydrogen could be produced using hydroelectric generation. A hydropower generation conversion system in this interconnected system converts mechanical energy into electrical energy, which is then used by water electrolysis to convert pre-treated saltwater into green hydrogen [54]. Dams can collect hydroelectric power with high efficiencies, and electrical energy can be converted into green hydrogen with a 48% efficiency that can be used for energy production [55]. However, the production and use of hydroelectric energy in the country appear to be behind schedule in terms of technology and capacity. Iraq has found places that have the potential to make 165 GW of hydroelectric energy [56].

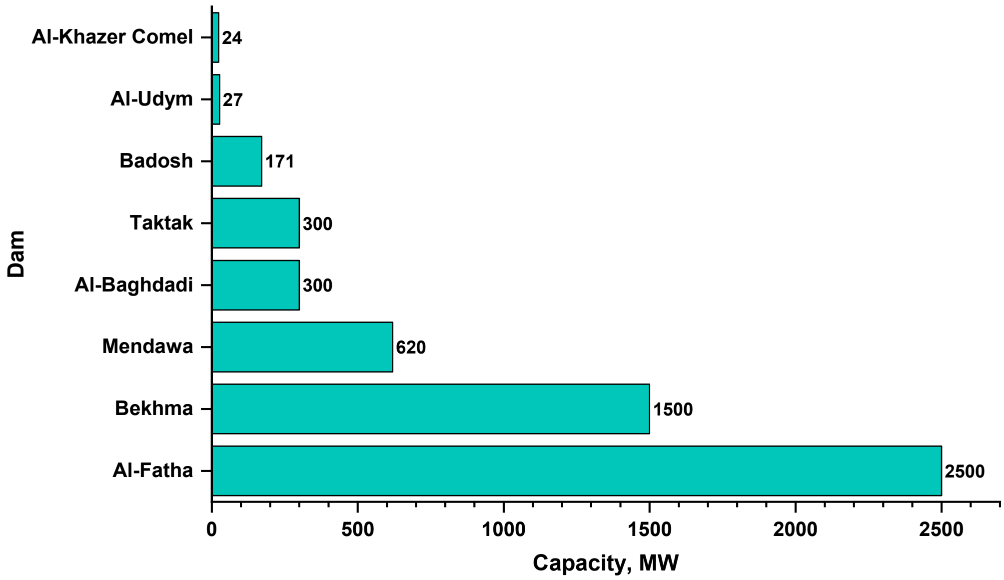

Figure 7. Planned hydropower dams by 2035 [53].

5.4. Hydrogen Production by Biomass Energy

Iraq is particularly biomass-rich. Regrettably, the accessibility of gas and oil as fuel resources has a detrimental impact on biomass-related research. The scientists have carried out a few experiments on the use of bioethanol and methanol in blended combustion engine fuels, such as gasoline and diesel [57]. Biomass was a natural energy source with numerous supplies and a cheap price in Iraq, and it was extensively employed to produce a variety of fuels and natural resources [58]. The method of producing hydrogen from biomass has garnered considerable interest [59]. In the categorization of biomass, algae, municipal solid waste, and wood were included [60]. Related to the ingestion of carbon dioxide throughout the growth phase, wood biomass is regarded as a high-quality carbon-neutral source of energy [61]. Furthermore, the ash percentage of biomass feedstocks was lower than that of microalgal biomass, and combining biomass feedstocks with waste food increased hydrogen production while decreasing exhaust emissions [62]. The effectiveness of producing green hydrogen using biomass was validated, and the output of green hydrogen was successfully increased by integrating inert boundary layer combustion technologies with wood biomass hydrogen production. The structure of porous media has a big effect on how wood biomass burns and how much hydrogen it makes. This is an area that has not been looked into enough, especially where inert and combustion boundary layers meet.

However, green hydrogen production in Iraq can be achieved using a combination of renewable energy sources. By leveraging its significant renewable energy potential, the country has the opportunity to become a leader in green hydrogen production in the region and contribute to the global transition to sustainable energy systems.

6. Current Challenges of Green Hydrogen Production in Iraq

Green hydrogen production has the potential to play a significant role in the country transition to a sustainable and low-carbon energy system. there are several challenges that need to be addressed to achieve this goal.

6.1. Infrastructural Limitations (Transportation, Storage, Distribution)

One of the significant challenges facing green hydrogen production is the lack of infrastructure to support transportation, storage, and distribution of hydrogen [63,64]. Green hydrogen is produced through electrolysis, which requires large amounts of electricity and water, and then needs to be transported and stored for future use.

- Transportation of hydrogen is challenging due to its low density, which requires significant space to transport the gas. To overcome this challenge, hydrogen can be compressed or liquefied, which requires additional infrastructure and investment. Currently, there is a lack of infrastructure for transporting hydrogen, which makes it challenging to move the gas from production sites to end-users.
- Storage of hydrogen is another significant challenge for green hydrogen production. Hydrogen is highly flammable and requires specialized storage facilities. Currently, there are limited options for hydrogen storage, and the existing infrastructure is not sufficient to meet the demands of green hydrogen production. This lack of infrastructure can limit the amount of hydrogen that can be produced and stored, ultimately limiting the potential for its use in the energy sector.
- Distribution is also a significant challenge for green hydrogen production. There is a lack of a comprehensive distribution network for green hydrogen, which makes it difficult to distribute the gas to end-users. This lack of a distribution network also makes it challenging for green hydrogen to be used as a transportation fuel. There is a need for the development of a robust and reliable distribution network to facilitate the use of green hydrogen across the country.

The infrastructural limitations related to transportation, storage, and distribution are significant challenges for green hydrogen production. Addressing these challenges will require significant investment in infrastructure and research and development to facilitate the adoption of green hydrogen as a clean and sustainable energy source.

6.2. Political and Regulatory Barriers

Political and regulatory barriers pose significant challenges for green hydrogen production [65,66]. These barriers can create uncertainty for investors and limit the development of green hydrogen projects, which can summarize as:

- The lack of a supportive regulatory framework: The absence of clear policies and regulations that support the development of green hydrogen production creates uncertainty for investors and limits the growth of green hydrogen projects. The lack of clarity in the regulatory framework can make it difficult for companies to make long-term investment decisions, leading to a lack of investment in the industry.
- Political instability: The ongoing conflict and instability in the region create uncertainty and limit investment in the energy sector, including green hydrogen production. Political instability can also increase the cost of project financing due to higher risk perceptions.
- Limited political will: The lack of political will to invest in the necessary infrastructure for green hydrogen production can limit the growth of the industry. This can be due to a lack of understanding of the potential benefits of green hydrogen, or competing priorities for limited government resources.
- Regulatory barriers: The existing regulatory environment may not be well-suited to support the development of green hydrogen production, which can make it challenging to secure the necessary permits and approvals for new projects. This can create additional costs and delays in project development, hindering the growth of the industry.
- Limited technical expertise: Another challenge for the growth of green hydrogen production is the limited technical expertise in the field. This can make it difficult to design, build, and operate hydrogen production facilities efficiently and safely.

Addressing political and regulatory barriers to green hydrogen production requires a supportive regulatory framework, a stable political environment, investment in necessary infrastructure, a comprehensive legal framework, and technical expertise.

6.3. Economic Feasibility and Investment Challenges

Green hydrogen production in Iraq faces significant economic feasibility and investment challenges that need to be addressed to unlock its full potential [67,68]. Here are some of the key challenges:

- High production costs: green hydrogen production is currently more expensive than conventional hydrogen production, making it less economically viable. The high production costs are mainly due to the high capital costs of the renewable energy technologies used to produce green hydrogen, such as solar, wind, or hydropower, and the limited economies of scale for production facilities.
- Lack of infrastructure: another major economic challenge for green hydrogen production is the lack of necessary infrastructure, such as hydrogen storage facilities, transportation systems, and distribution networks. Building this infrastructure requires significant investment, which can be a barrier to entry for investors.
- Limited access to financing: access to financing is crucial for developing green hydrogen production projects. However, limited access to financing, especially long-term and low-cost financing, can be a significant challenge for the industry. This is because green hydrogen production is a relatively new and unproven technology that may not yet be attractive to traditional lenders or investors.
- Uncertainty in the market: the lack of a clear market for green hydrogen can also be a challenge for investors. The demand for green hydrogen is not yet well-established, and the pricing mechanisms for green hydrogen are not yet fully developed. This makes it difficult for investors to assess the economic viability of green hydrogen projects and the long-term profitability of their investments.
- Political risk: Political risk is another factor that can impact the economic feasibility of green hydrogen production. The country geopolitical situation and ongoing conflicts can create uncertainty, which can impact the investment climate and deter potential investors.

Addressing these challenges will be critical to realizing the potential of green hydrogen production in Iraq as a sustainable and viable energy source.

7. Visibility of Hydrogen Utilization in Iraq

Green hydrogen production from renewable energy sources such as wind and solar using water electrolysis technologies is expected to be at the heart of the energy transformation required to meet net-zero issues. Furthermore, water electrolysis is a well-established electromechanical technology for the creation of green hydrogen that must be widely used in order to reduce production costs while maintaining high efficiency. In order to manufacture viable, sustainable hydrogen and fulfil the worldwide net-zero challenge, important upgrades and technologies are necessary. The country youthful population and direct government will to attain zero emissions provide a chance for the growth of a hydrogen-based economy. In accordance with the country energy strategy for 2020–2035, the following are potential green hydrogen applications:

Mobility is a vital sector that connects population and commercial centres throughout the cities; it includes road, air [69]. Through its modernization programme for government-owned vehicles, the government is now making the transportation system less polluting by switching to more environmentally friendly forms of public transportation. Currently, the government is reducing emissions in the transportation sector by adopting more sustainable means of public transportation into its regulated utility vehicle development programme [70]. In keeping with the administration intention to promote green hydrogen production, green hydrogen may be used to create power for fuel cell vehicles [71]. Due to its low weight and high energy content, hydrogen would reduce the quantity of fuel necessary to raise an aircraft at the commencement of a flight and increase the distance an aircraft could go without refuelling [72]. Furthermore, green hydrogen is a viable solution for the marine sector since its distribution network paths emit much less carbon dioxide than traditional fuels, including such heavy petroleum oils [73].

- The inconsistent electrical supply and poor energy infrastructure used by residents on the country. In addition, the considerations related to the three distinct domestic uses. More over half of the respondents either agreed or strongly agreed that they would be content to utilise hydrogen for home heating, hot heating water, and cooking. Regression analysis studies were conducted to determine the factors that are associated with each of the applications [74]. As was the case with prior models, each dependent variable, including cooking, space heating, and hot heating water et al. All three forms of use were connected with both health and environmental advantages. Individuals are more likely to accept the replacement of natural gas with 90% hydrogen in existing gas networks as a result of more subtleties in their approve for hydrogen during cooking. In the case of space heating and water heating, meanwhile, they are more likely to approve a 12% hydrogen mix in existing natural gas networks [75,76]. In addition, individuals are more inclined to accept hydrogen generated from fossil fuels as an intermediate step.
- Green hydrogen may be included in industrial processes. Chemical compounds: nitrogen, polyurethane, and polyurethane manufacturing; perfecting: experimental and geothermal procedures; steel production; the direct decrease of steel via hydrogen for electricity; and low-carbon steel manufacturing; as well as other industrial uses including glass industrial production, packaged foods, electronic components, and liquid fuel for aerospace structures [77]. The petroleum refinery sector has the biggest need for hydrogen, followed by the manufacturing of ammonia, fertiliser, alcohol, and other petroleum—based products, as well as industrial heat sources [78]. Previously, Qethara company began construction on an integrated conventional and green hydrogen production plant since 2020 [79]. In addition, a carbon capture plant will be established to convert carbon dioxide byproducts for industrial uses, including on-site fuel production or sale to makers of dry ice and carbonated beverages [80]. When the global market for gasoline increases and green hydrogen infrastructure becomes accessible in the United States in the near future, blue hydrogen will facilitate the use of green hydrogen.

8. Roadmap for Green Hydrogen Production in Iraq

Developing a roadmap for green hydrogen production would require a coordinated effort by the government, private sector, and international partners. Here are some key steps that could be taken to develop a roadmap for green hydrogen production:

- **Set targets:** the government could set targets for the production of green hydrogen in the country. This would involve establishing a timeline for the development of renewable energy infrastructure, including solar and wind farms, as well as the production of green hydrogen.
- **Develop regulatory framework:** the government could establish a regulatory framework to support the development of green hydrogen production. This could include policies to encourage investment in renewable energy infrastructure, as well as regulations to ensure the safety and sustainability of hydrogen production.
- **Attract investment:** to attract investment in green hydrogen production, the government could offer incentives such as tax breaks, subsidies, and streamlined permitting processes. International partners with expertise in renewable energy and hydrogen production could also be invited to invest in the country.
- **Build infrastructure:** developing renewable energy infrastructure is essential for green hydrogen production. The government could work with private sector partners to build solar and wind farms, as well as hydrogen production facilities. The country's natural gas reserves could also be leveraged as a feedstock for hydrogen production.
- **Create jobs:** developing a green hydrogen industry could create jobs, particularly in the areas of renewable energy, hydrogen production, and energy storage. The government could work with private sector partners to establish training programs and create job opportunities in these areas.

- **Collaborate internationally:** The country could collaborate with international partners to develop its green hydrogen industry. This could include partnerships with countries with advanced renewable energy infrastructure and hydrogen production capabilities, as well as international organizations such as the International Renewable Energy Agency (IRENA).
- **Demonstrate success:** the success of green hydrogen production will depend on demonstrating that it is a viable and sustainable alternative to fossil fuels. The government could work with private sector partners to establish demonstration projects and showcase the benefits of green hydrogen production to investors and other stakeholders.

By setting targets, developing a regulatory framework, attracting investment, building infrastructure, creating jobs, collaborating internationally, and demonstrating success, the country could position itself as a leader in the global transition to a low-carbon economy.

9. Long-Term Map for Green Hydrogen Production

Considering the potential for supply and many routes of usage, as well as the promise made unite nations to cut emissions by 40% by 2030 and attain low emissions by 2050, a series of activities may be taken to transition to a green production of hydrogen. Initial demand for green hydrogen is required to enable its considerable quantity from sources of renewable energy. It is proposed that green hydrogen reach in three stages, as seen in Figure 8.

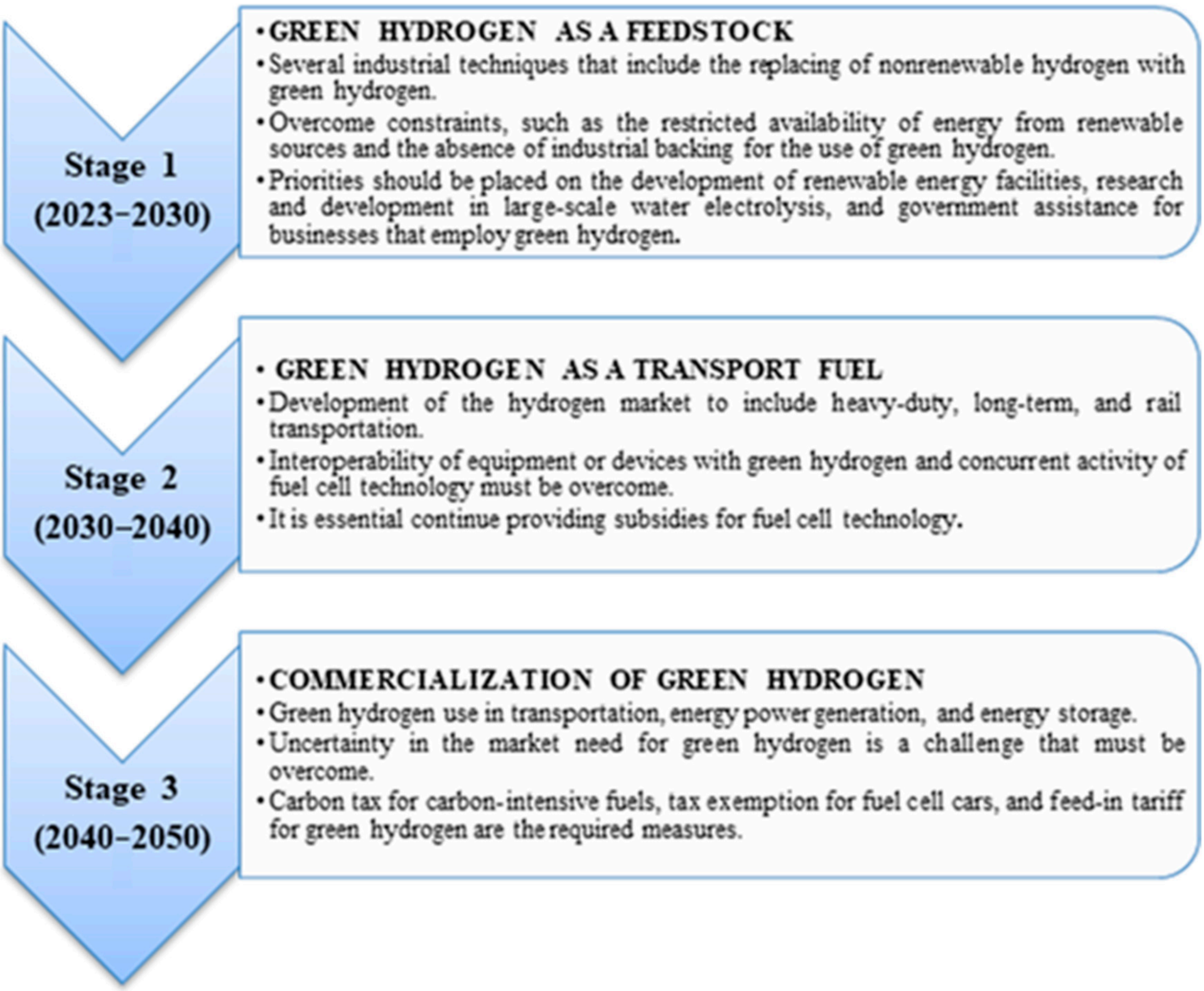

Figure 8. The green hydrogen economy roadmap for (2023–2050) in Iraq.

- **The first stage**: sustainable hydrogen will replace fossil fuel-based hydrogen in various applications of chemical products. Winds, solar, hydropower, and biomass are the primary renewable energy that may be used to produce green hydrogen [81]. Using hydrogen in a variety of applications, such as the separating of metallic elements from their oxides, the creation of glasses, and the manufacturing of mayonnaise or vegetable shortening may minimise carbon dioxide emissions [82]. The manufacture of chemicals offers a solid market for importing green hydrogen since it gives a particular, predictable chance to sell green hydrogen and even produce it in chemical plants, pending the development of other, affordable forms of green hydrogen technology. Accelerate the development and research of massive water electrolysis and the expansion of renewable energy facilities in order to produce green hydrogen for industrial use. The objective of the first stage is to offer more time for growing the supply of green hydrogen and developing its infrastructure for widespread energy uses in subsequent stages.
- **The second stage**: With the availability of resources and technology for renewable energy, the industry for green hydrogen will extend outside the industrial sector. This shift involves decarbonizing heavy-duty, long-distance, and marine transportation. Note that the topography on each individual in the Iraqi archipelago is distinct. Consequently, the usage of reduced to zero-carbon cars is now restricted to metropolitan regions with mostly flat topography and short-distance transportation [83]. In this stage, renewable hydrogen may power any land-based vehicle with simple modifications to its internal combustion engine.
- **The third stage:** fuel cell technologies are commercialised, may be reached in which sustainable hydrogen can be employed in fuel cell automobiles, Hydrogen may be used in a hydrogen-powered fuel cell to generate energy, which can then be used in a variety of applications, including electric vehicles, industrial applications, and residential implementations. The fuel cell may be put in a car to generate power for vehicle operation. Fuel cell systems are intended for stationary usage in big central power plants and distributed generation of electricity. This technique could be applied to urban and rural homes and structures [84]. Fuel cells are a viable solution for converting hydrogen into energy that may be utilised to power an electric car. In contrast to the burning of hydrogen in petroleum engines (gasoline and diesel), hydrogen may be utilised to create electricity using various kinds of cells. Using hydrogen in fuel cells will aid in achieving carbon neutrality by 2050 and reduce emissions into the environment. In order for fuel cells to gain momentum in the market, their price, reliability, and availability must be established. Few automakers produce fuel cell automobiles, and the automobiles are not widely accessible throughout the globe. Hybrid automobiles are now accessible on the market; fuel cell automobiles are not.

10. Difficulties and Repercussions for the Sustainable Hydrogen Production and Utilization

Although hydrogen has enormous possibility of replacing traditional fossil fuels, several difficulties must be overcome for the process to go smoothly. This section has described the current obstacles hydrogen faces as a substitute for conventional fuels. The current situation in Iraq and the globe capacity for producing, storing, and distributing hydrogen falls well short of what will be needed in the future. Demand-driven development of hydrogen-related facilities, comprising production, storage, and distribution to end users, is required. The framework for hydrogen distribution, storage, and supply is not completely established anywhere in the globe to meet the demand that would result from the gradual conversion of automobiles to use hydrogen fuel or fuel cells. Compared to traditional gasoline stations, the total number of hydrogens refueling stations globally is quite low.

- As green hydrogen is electrolyzed, condensed, or transferred to different carriers, delivered, and used in fuel cell technology, a substantial amount of energy is lost due to technical difficulties. If such inefficiencies are not addressed, they will necessitate a significant use of renewable energy sources to power hydrogen electrolyzers capable of competing with end to electricity [85]. Additionally, storage and transfer of hydrogen might be difficult. It must be stored in a porous substance at high pressure and very cold temperatures. Hydrogen has a higher potential for leakage than fossil fuels or methane and may cause pipeline steel to become brittle. Using hydrogen in a fuel cell requires ultra-high purities. When using bioenergy as a raw resource, this degree of purity requires the use of clean water for hydrolysis or other purification methods. Since fuel cells are vulnerable to a range of pollutants, rising hydrogen should be utilised [86].

- Public acceptability and understanding are further obstacles to the use of green hydrogen. Before a technology may grow, it must be accepted by a wider population. To address all of these concerns, there will need to be a large-scale public awareness campaign that includes detailed health and safety analyses as well as changes to the laws.
- For green hydrogen, technological and economic viability are formidable obstacles. Another aspect is the cost of green hydrogen generating technologies. The community potential customers should be able to pay for the cost of the connected solution that would make green hydrogen. With the exception of industrialised nations, which face the high cost of trying to generate hydrogen from renewable electricity, particularly for large implementations, emerging economies have a broadening natural resource availability for generating electricity, which could reduce the price of hydrogen production when distance and requirement size are considered [87]. Furthermore, even in nations with plentiful renewable resources, power accounts for 40–60% of the cost of production, whereas catalysts and the rest of the system are very inexpensive [88]. The administration should work with more well-known firms that have been involved in making green hydrogen infrastructure and services in order to come up with a comprehensive plan for the growth of green hydrogen on that market and the expansion of such infrastructure.
- Concerning societal problems, among the most important obstacles to the commercialization of green hydrogen have been concerns about the fuel security [89], despite the fact that hydrogen is more diffuse than fossil fuels and petroleum. Stakeholders have different points of view, but they all agree that populations are helped by providing access, local public outreach, building geographical skills, protecting biodiversity, and providing protection and consequentialist benefits to society. All of these things are important to the success of the hydrocarbons industry [89]. For industrialised nations with a high social insurance index, the danger of public opposition to an energy system transition is theoretically minimised [90]. Consequently, the government should improve public understanding and awareness of renewable fuels through organised initiatives and public statements in newspapers [91–96].
- Hydrogen is acknowledged as the perfect energy carrier since it neither improves air quality nor contributes to climate change. Hydrogen and electricity might work together to create appealing transportation and energy generating choices. Interconversion between any of these two sources of energy supports on-site use of green hydrogen to create electricity, with the electricity supply grid providing energy transmission, distribution, usage, and hydrogen reproduction as required. Still many challenging with green hydrogen production and usage as a future energy source is that it is hard to make a lot of it in a way that does not hurt the environment and is sustainable.

11. Initiatives and Support Arthurites for Green Hydrogen Regulations

The Iraqi arthurites implement a variety of programmes to support and promote the use of hydrogen production and renewable energy sources. Below are the most important recommendations:

- Develop economic freedom and competition that permit broad participation in order to guarantee the viability of green hydrogen and renewable energy implementation.
- Effectively perform market tasks to guarantee the variety of resources available.
- Reliability in the exchange of energy statistics between domestic and international enterprises.
- Provide the required financial resources for renewable power projects.
- Issuing plans, as well as policies, that secure corporations commitments to transmission and distribution by acquiring electricity produced through renewable resources and implementing laws that may handle an agreed-upon amount of green hydrogen production.
- Reduce taxes and import duties on equipment connected to renewable energy grants or loans. A pricing platform provides the purchase and sale of "certificates" for sustainable energy, enabling providers to meet their commitments.
- Urban planning initiatives and initiatives must incorporate the distribution of lands necessary to develop power production plants using sources of renewable energy for green hydrogen production.
- Provide assistance to minimise the amount of power generated from fossil fuels via the technical development of solar energy. In addition, a development of the solar electricity sector with appealing pricing for renewable energy customers and providers is required.
- Raising public knowledge, especially on the financial advantages, regulatory standards, and potential impacts of renewable energy production.
- Development of supporting policies, such as regulations that may enforce prices and provide real assistance to those that install renewable energy technology.
- Information provided on the deployment of solar and wind energy equipment and technical information concerning capacity development, as well as assistance for research into renewable energy.
- The planning and execution of renewable energy sources by the Iraqi department of energy must be encouraged in order to reach the primary objective of boosting renewable energy-based electricity generation by roughly 9.4% by 2025, which will also have an effect on CO_2 emissions.

12. Conclusions

The development of green hydrogen production is gaining attention worldwide as an alternative source of energy to reduce carbon emissions and mitigate climate change. Iraq is one of the countries that has a high potential to become a major player in the green hydrogen market. The study highlights that Iraq has abundant renewable energy resources, particularly solar and wind energy, that can be utilized to produce green hydrogen. The renewable energy potential remains largely untapped, and the country has yet to fully explore the benefits of developing a green hydrogen industry.

The study proposes a roadmap that includes both short-term and long-term goals to establish a legal framework, attract foreign investment, develop a skilled workforce, and create an enabling environment for technology transfer. The roadmap proposed in the study highlights the importance of partnerships and collaboration between the government, private sector, and international organizations. The involvement of these stakeholders is critical to the successful implementation of the roadmap. The study also identifies the potential economic benefits of green hydrogen production in Iraq, such as job creation, energy security, and reduced dependence on fossil fuels. The results provide valuable insights and recommendations for policymakers and industry leaders in Iraq and other countries seeking to develop their green hydrogen industries. The study's recommendations align with global efforts to promote sustainable development and mitigate climate change. As countries worldwide shift towards renewable energy, the development of green hydrogen production in Iraq could play a significant role in reducing global carbon emissions. The proposed roadmap and strategic policy towards green hydrogen production in Iraq are essential for the country to realize its potential in the green hydrogen market. The successful implementation of the roadmap could pave the way for Iraq to become a leader in green hydrogen production, create employment opportunities, and support the country's transition to a low-carbon economy.

The present infrastructure of Iraq is insufficient to provide the country total energy needs. As a result, a hydrogen infrastructure is required to meet demand. There is no description of the infrastructure for the production, delivery, and storage of green hydrogen. The creation of efficient manufacturing, transport, administration, and storage requires more study.

13. Future Outlook

Iraq is a country that has significant potential for green hydrogen production due to its abundant renewable energy resources and favorable geographic location. This article explored a roadmap with strategic policies towards green hydrogen production in the country. The country has a vast solar potential, with an average solar radiation of 5.7 kWh/m^2 per day [34]. The country also has significant wind resources, especially in the western and northern regions. With an estimated 80 billion cubic meters of natural gas flared annually, the country has a significant opportunity to reduce greenhouse gas emissions and utilize this wasted resource for green hydrogen production [31]. Therefore, Iraq has the potential to become a major player in the global green hydrogen market. To achieve this, country must develop a future step that will enable the country to fully exploit its renewable energy potential and develop a green hydrogen industry.

- Set ambitious targets for renewable energy deployment and green hydrogen production. Iraq should aim to produce 10% of its total energy from renewable sources by 2030 and to become a net exporter of green hydrogen by 2040–2050. These targets should be accompanied by specific policies and incentives to support the development of the renewable energy and green hydrogen industries.
- Create a regulatory framework that supports the deployment of renewable energy and green hydrogen. The country should establish a legal and regulatory framework that provides clarity and certainty for investors in the renewable energy and green hydrogen sectors. This framework should include regulations on grid connection, power purchase agreements, and pricing mechanisms for renewable energy and green hydrogen.
- Invest in research and development (R&D) to reduce the costs of renewable energy and green hydrogen production. The country should allocate funds to R&D programs that focus on improving the efficiency of renewable energy systems, reducing the cost of electrolysis, and developing new technologies for hydrogen storage and transportation.
- Promote the development of a green hydrogen ecosystem. The country should encourage the establishment of a domestic green hydrogen industry by providing incentives for companies to invest in green hydrogen production and developing a local supply chain for green hydrogen. This could include the establishment of green hydrogen clusters or industrial parks where companies can co-locate and share infrastructure and services.
- Develop partnerships with international organizations and other countries to share knowledge and experience in renewable energy and green hydrogen. The authorities should seek partnerships with countries that have already developed a green hydrogen industry, such as Germany, Australia, and Japan, to learn from their experience and to access their technology and expertise.

Finally, the country has significant potential for green hydrogen production, and a strategic policy roadmap is necessary to fully exploit this potential. The roadmap should include ambitious targets, a supportive regulatory framework, investment in R&D, promotion of a green hydrogen ecosystem, and partnerships with international organizations and other countries. By following this roadmap, Iraq can become a major player in the global green hydrogen market and contribute to the transition to a low-carbon economy.

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