Solar Energy
And Sustainable Development
Refereed, biannual scientific journal issued by:
The Libyan Center for Solar Energy Research and Studies

Review paper on Green Hydrogen Production, Storage, and Utilization Techniques in Libya

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ARTICALE INFO.

Article history:
Received 26 December 2023
Received in revised form 26 October 2023
Accepted 4 February 2024
Available online 11 February 2024

KEYWORDS

Green hydrogen, renewable energy, types of hydrogen, preparation methods, Utilization techniques.

ABSTRACT

the world is currently facing energy-related challenges due to the cost and pollution of non-renewable energy sources and the increasing power demand from renewable energy sources. Green hydrogen is a promising solution in Libya for converting renewable energy into usable fuel. This paper covers the types of hydrogen, its features, preparation methods, and uses. Green hydrogen production is still limited in the world due to safety requirements because hydrogen has a relatively low ignition temperature and an extensive ignition range and is considered a hazardous element, the lack of infrastructure in Libya, as well as the high cost of production currently.

However, the production costs of one megawatt of green hydrogen and fossil fuels are insignificant. This suggests that electricity production from green hydrogen could become an economic competitor to fossil fuels in Libya. This is due to the cost of adding renewable energy to the public electricity grid. Also, the production of gray hydrogen is possible in Libya because of oil through the installation of systems for converting methane gas and capturing carbon dioxide gas.

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DOI: https://doi.org/10.51646/jsesd.v13i1.165

ورقة مراجعة حول تقنيات إنتاج الهيدروجين الأخضر وتخزينه واستخدامه في ليبيا

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ملخص: يواجه العالم حاليا تحديات متعلقة بالطاقة بسبب تكلفة وتلوث مصادر الطاقة غير المتجددة والطلب المتزايد على الطاقة من مصادر الطاقة المتجددة. ويعد الهيدروجين الأخضر حلا واعدا في ليبيا لتحويل الطاقة المتجددة إلى وقود قابل للاستخدام. تغطي هذه الورقة أنواع الهيدروجين وخصائصه وطرق تحضيره واستخداماته. لا يزال إنتاج الهيدروجين الأخضر محدودا في العالم بسبب متطلبات السلامة لأن الهيدروجين له درجة حرارة اشتعال منخفضة نسبيا ومدى اشتعال واسع ويعتبر عنصر خطر، ونقص البنية التحتية في ليبيا، بالإضافة إلى ارتفاع تكلفة الإنتاج حاليا. ومع ذلك، فإن تكاليف إنتاج ميجاوات واحد من الهيدروجين الأخضر والوقود الأحفوري ضئيلة. وهذا يشير إلى أن إنتاج الكهرباء من الهيدروجين الأخضر يمكن أن يصبح منافسا اقتصاديا للوقود الأحفوري في ليبيا. ويرجع ذلك إلى تكلفة إضافة الطاقة المتجددة إلى شبكة الكهرباء العامة. كما أن إنتاج الهيدروجين الرمادي ممكن في ليبيا بسبب النفط من خلال تركيب أنظمة لتحويل غاز الميثان والتقاط غاز ثان أكسيد الكربون.

1. INTRODUCTION

A growing number of nations have committed to reaching net zero emissions in recent years. 88% of the world's greenhouse gas emissions, had declared net zero goals. Global temperatures have already risen by 1.1°C since pre-industrial times as a result of anthropogenic emissions. Most people agree that achieving net zero by 2050 will raise the likelihood of restricting the rise in temperature to 1.5°C [1]. Because of this increasing emphasis, emissions from all energy-related end use need to be reduced. Where alternative solutions are less developed or more expensive, such as heavy industrial, long-haul transportation, and seasonal energy, hydrogen will be required to decarbonize end users, even though energy efficiency, electrification, and renewables can deliver 70% of the mitigation needed. Libya can lead the world in renewable energy. It has a very high daily solar radiation rate, around 8.1 kWh/m^2/day in the southern region and 7.1 kWh/m^2/day on the flat coastal plain [2]. According to a study published in the Journal of Renewable Energy, With these uses in mind, hydrogen may account for 12% of the total energy demand and 10% of the mitigation required to meet the 1.5°C scenario. Libya could produce more than five times the consumption if used PV systems as possible if it employed a PV system for just 0.1% of its space area.

Libya's economy is heavily dependent on the extraction of natural gas and oil, making structural changes challenging. Libyan people lack a workforce with the necessary skills to build and maintain green hydrogen infrastructure. The state can increase its current revenue base by utilizing sustainable and renewable energy sources and investing in green hydrogen with the appropriate funding and training. Using the renewable energy sources found in this oil-rich nation, Libya can meet all of its electrical needs, power the general grid, charge electric vehicles, and export a sizable amount of energy to its neighbors in southern Europe [3].

The possibility of integrating renewable energy into the Libyan transport system will increase the expansion of transit commerce. Also, the production of electricity from renewable energy sources close to the places of electricity consumption is provided by the prospect of integrating clean energy into the Libyan transport system through the integration of photovoltaic cells in the Libyan grid [4,5]. In Libya, solar PV modules installed at large stations can supply up to 100% of the country's transport system needs, Libya is a bridge connecting Africa and Europe, with any excess power feeding the public grid. political backing for renewable energy sources integrated into the grid will help Libya's transit trade grow. The Libyan General Electricity Company signed a contract with Total to carry out initiatives aimed at utilizing the energy from solar systems with a maximum 500MW capacity to produce power, its production will be injected into the general electricity grid at a price of 10¢/kWh [6]. Libya's first solar energy project will be put into action to address the problems facing the country's electrical industry. The nation experienced a daily electrical shortage of over 2,500 megawatts. The majority of Libyans now depend on private generators as a result. By 2025 and 2030, respectively, the General Electricity Company hopes to increase its capacity to 14,834 MW and 21,669 MW [7].

It's important to note that, on average, Libya's coastal regions receive an average of 3,500 hours per year of sunshine and 140,000 TWh of annual power[8] in Fig 1. If Libya exploits a PV to cover only 0.1% of its area, it would still be able to generate a significant amount of solar energy due to its large landmass. PV technology has the potential to greatly benefit Libya's energy needs and reduce its reliance on fossil fuels. Libya could create about five times as much electricity from solar power as from crude oil if it covered just 0.1% of its geographical area with solar panels. The oil and gas industry is the main source of income for the country's economy, accounting for approximately 95% of export earnings, 25% of the GDP, and 60% of public sector pay.

Libya has one of the highest per capita GDPs in Africa thanks to its tiny population and significant energy sector earnings. According to Responding to Climate Change, Libya has the potential to grow into a major player in renewable energy. It has a very high daily solar radiation rate; in the south, it is approximately 8.1 kWh/m^2/day, and on a flat coastal plain, it is approximately 7.1 kWh/m^2/day.

Compared to Libya, the UK has less than half of that amount, at roughly 2.95kWh/m^2/day.

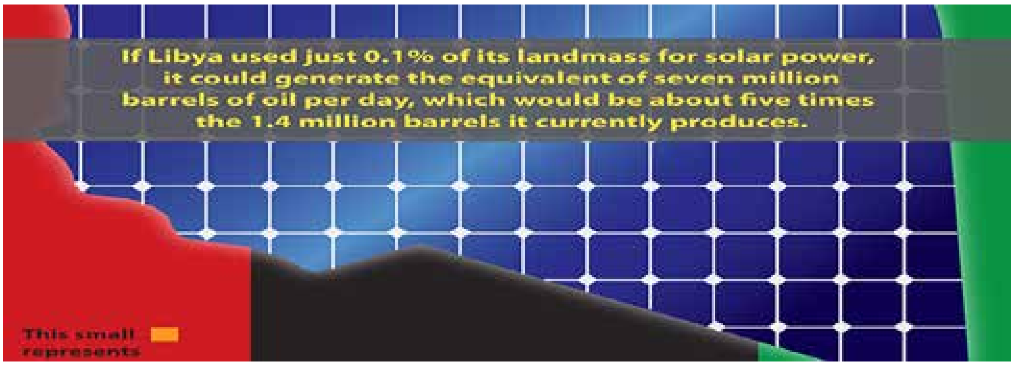

Fig 1. Suppose Libya exploits a PV to cover only 0.1% of its area [9].

As a result of the increase in the price of electricity produced either from natural gas or Oil: the world is moving towards producing electricity from renewable energy sources, and green hydrogen. This shift towards renewable energy sources and green hydrogen is driven by the need to reduce carbon emissions and mitigate the impact of climate change. Governments, businesses, and individuals are investing in solar, wind, hydro, and geothermal energy to power their homes, offices, and industries. Green hydrogen, produced through electrolysis using renewable energy, is also gaining traction as a clean and sustainable alternative to traditional fossil fuels. As technology advances and economies of scale are achieved, the cost of renewable energy and green hydrogen is expected to become more competitive with traditional forms of electricity generation. This transition towards cleaner and more sustainable energy sources is crucial for a more sustainable and environmentally friendly future. Hydrogen-fueled electric generators are a promising alternative to traditional fossil fuel generators. A hydrogen-fueled generator set that can run on natural gas blends with up to 25% hydrogen by volume. These generator sets are highly efficient, have lower greenhouse gas emissions compared to natural gas and diesel engines, and have the same long overhaul intervals as natural gas-fueled assets. Retrofit kits are also available for existing generator sets. The Libyan government of national unity issued a decision setting electricity generators from traditional fossil fuel sale prices based on nine tranches. The decision aims to ensure fair pricing for electricity consumers and to address the financial challenges facing the electricity sector in Libya.

The nine tranches are designed to take into account the varying consumption levels of different consumer groups, to promote energy efficiency and conservation. Table (I) sets the sale prices of electric energy in Libya on the following prices, This new pricing system is expected to contribute to the sustainability of the electricity sector and to improve the overall reliability of the power supply in the country [40].

TABLE I. Setting the sale prices of electric energy in Libya dirhams per kWh.

NO.	Type of Use	Cost (dirhams per kWh)
1	Household	40
2	Household Bank Installments or Salary	25
3	Commercial	80
4	Light Industrial	60
5	Heavy Industrial	45
6	Public Utilities	135
7	Street Lighting	135
8	Small Farmers	40
9	Large Farmers	45

A growing number of nations are using more renewable energy (RE) sources to diversify their energy mix to mitigate the negative environmental effects of burning fossil fuels. At least half of the energy produced worldwide. The Industrial Revolution—which has the potential to boost income levels and enhance human well-being—must come from zero-emission technology to combat climate change and population increase [10]. Due to urbanization, economic expansion, and population growth, the world's energy demand has been rising continuously. The need for energy will only grow as the global population is predicted to reach approximately 9.7 billion people by the year 2050. Meeting this increasing energy demand will require a mix of solutions, including renewable energy sources, energy efficiency measures, and advancements in technology. It will also necessitate a shift towards more sustainable and environmentally friendly energy practices to mitigate the impact on the planet. As we look towards the future, it is crucial to prioritize the development and implementation of clean energy solutions to ensure a sustainable and secure energy supply for generations to come [11].

Large volumes of greenhouse gases (GHGs), mostly carbon dioxide (CO_2), are released during the combustion of fossil fuels, and these GHGs play a role in climate change and global warming. Rising sea levels, more frequent and severe weather events, and a decline in biodiversity are all effects of global warming. The need to reduce greenhouse gas emissions and transition to renewable energy sources has become increasingly urgent to mitigate the impacts of climate change. Governments, businesses, and individuals all have a role to play in addressing this global challenge. Implementing policies and practices that promote energy efficiency, investing in renewable energy technologies, and supporting sustainable land use are all crucial steps in combating the effects of global warming. We must work together to protect the planet for future generations [12].

Many nations have begun to invest in renewable energy sources in response to the escalating worries about the environment and energy security. Clean energy sources that emit little to no greenhouse gases, such as hydroelectric power, solar power, and wind power, contribute to lowering the energy sector's overall carbon footprint. As a result, many countries are now focusing on developing and implementing policies and incentives to promote the use of renewable energy. This shift towards clean energy not only helps to reduce carbon emissions but also creates new job opportunities and stimulates economic growth. With advancements in technology and increasing investment in renewable energy infrastructure, the future looks promising for a more sustainable and environmentally friendly energy sector [13].

The increasing need for clean, sustainable energy sources has sparked technological innovation in the areas of renewable energy transmission, storage, and production. In this context, green hydrogen's high energy density, environmental friendliness, and adaptability to a wide range of uses have made it an appealing clean energy carrier. Green hydrogen can be produced through various methods, including electrolysis of water, reforming of natural gas, and biomass gasification. Its versatility allows for its use in fuel cells for transportation, heating, and electricity generation. As the demand for clean energy continues to grow, green hydrogen is positioned to play a crucial role in the transition to a more sustainable energy future [14].

Green hydrogen presents a viable resolution to the obstacles confronting the energy industry. It can make a substantial impact on the worldwide shift towards a low-carbon, sustainable future by seamlessly merging with renewable energy sources and mitigating the intermittent problems frequently linked to them. Hydrogen's versatility and abundance make it an attractive option for addressing energy challenges. Its potential to be used in various sectors such as transportation, industry, and power generation further solidifies its position as a key player in the transition to a greener economy. Fig 2. Showing the advancements of green hydrogen production and storage technologies, the prospects for its widespread adoption continue to improve, offering a promising solution to the global energy dilemma.

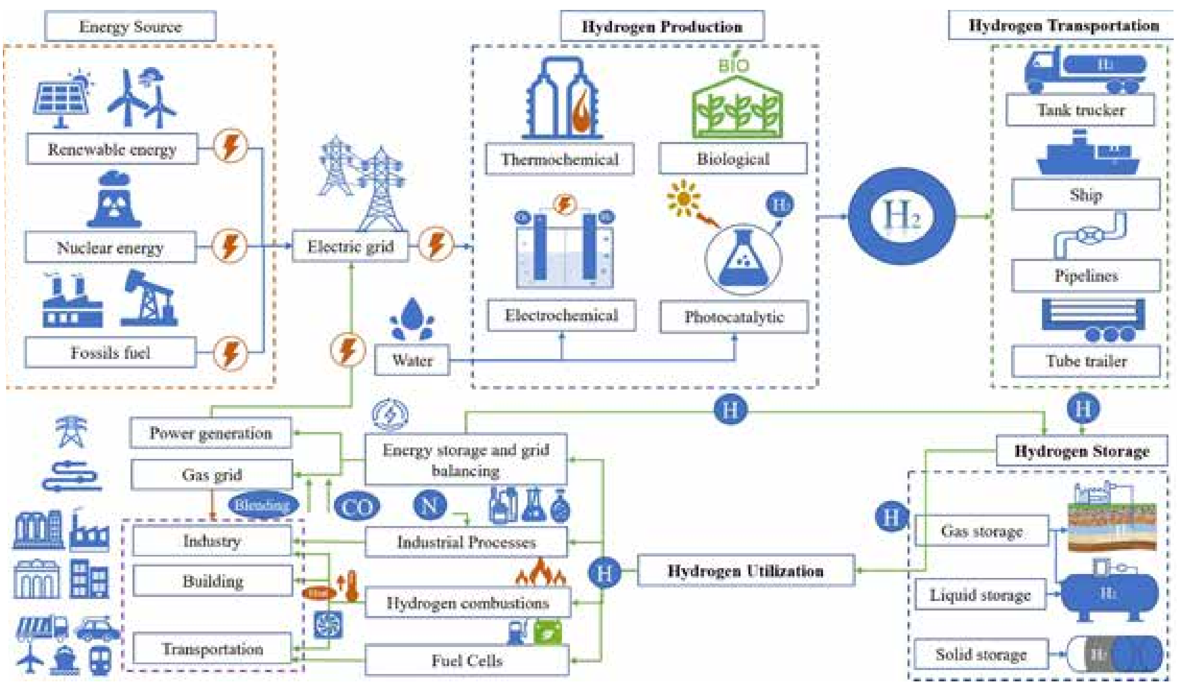

Fig 2. The advancements in the manufacture, transportation, storage, and use of hydrogen [15].

Putting hydro turbines in wastewater treatment plants' intake and output pipelines and using the sludge left over after treatment as a source for biogas production—which can be utilized to produce electricity—as well as using the sludge as a byproduct of the process. The leftovers from the fermentation process are then utilized as organic fertilizer to enhance agricultural land quality.

The treated water is then used to irrigate decorative plants in the roads, gardens, and forests. The study suggested a hybrid system at the wastewater treatment facility in Gharyan that consists of an electric generator powered by biogas and a hydroelectric station. because the city stands out for being situated at a height of roughly 713 meters above sea level [16]. As environmental degradation and the limited supply of fossil fuels, such as diesel, grow more concerning, the hunt for sustainable alternative energy sources is underway. Because it is widely available and can produce clean energy, hydrogen fuel has become an attractive alternative. But diesel is still widely used in the world's infrastructure today, especially in the transportation industry. tries to present a thorough comparison between diesel and hydrogen fuel in TABLE II, offering insights into their applicability and usefulness.

TABLE II. Comparisons between fuels (fuel and diesel) and hydrogen.

Comparison	Fuel and Diesel	Hydrogen
Definition	One kind of fossil fuel that comes from crude oil is diesel. Diesel engines, which are mostly found in internal combustion engines, burn fuel to produce mechanical energy. Although they are renowned for having a high energy density, their operation also results in the production of particulate matter, nitrogen oxides (NOx), carbon dioxide (CO_2), and other pollutants.	The utilization of hydrogen gas (H_2) as a power source is referred to as hydrogen fuel. There are other ways to create hydrogen, such as natural gas reforming and electrolysis. It is an environmentally benign energy source because, when used in fuel cells, it reacts chemically with oxygen to produce electricity, with the only byproducts being heat and water.
Environmental Impact	Diesel engines release particulate matter, NOx, CO_2, and other pollutants into the atmosphere, which greatly contributes to air pollution. Climate change and several health problems have been connected to these emissions. Although efforts have been made to lessen this impact—such as by integrating biodiesel and improving engine designs—diesel's overall environmental footprint is still troublesome.	The main benefit of hydrogen fuel over diesel is that it is more environmentally friendly. Hydrogen emits no pollutants when used in fuel cells; the sole result is water vapor. However, depending on the process, emissions may be connected to hydrogen production. Green hydrogen provides an entirely clean fuel lifecycle and is generated via electrolysis using renewable energy.
Economic and Energy Efficiency	Diesel is favored for long-distance transportation and heavy machines due to its high energy density, which implies that it provides a lot of energy per unit volume. Another well-known quality of diesel engines is their dependability and durability. Diesel has a financial edge over new fuels like hydrogen due to the vast infrastructure already in place for its manufacturing, distribution, and retailing.	Diesel-powered internal combustion engines are generally less efficient than hydrogen-powered fuel cells. Higher efficiency rates result from their direct conversion of the chemical energy in hydrogen into electricity without combustion. Diesel is a well-established and mature fuel market, and its prices are now lower than those of hydrogen production, storage, and distribution.

Prospects & Opportunities for the Future	It appears that diesel will continue to evolve rather than go extinct. Diesel is predicted to continue playing a role as advances in technology, such as biodiesel and cleaner diesel engines, occur, especially in industries where engine robustness and energy density are critical.	The hydrogen industry is expanding as a result of rising climate change concerns and technological advancements. Globally, corporations and governments are investing in hydrogen technology and infrastructure to replace fossil fuels like a diesel with hydrogen soon.

Diesel's current economic advantage and energy density make it an essential component of the Libya energy mix, even if hydrogen fuel offers substantial advantages in terms of environmental effect and potential for improved efficiency. But as part of a varied and sustainable energy mix, hydrogen will probably play a bigger role in the Libyan economy soon.

A. Main contribution

The contribution provided in this article is an overview of the different types of hydrogen, their key features, various preparation methods, and potential uses in the context of Libya's energy landscape. By understanding the characteristics and applications of green hydrogen, stakeholders in Libya can explore its potential to contribute to a more sustainable and environmentally friendly energy future.

B. Outline

The remaining sections in the article are organized as follows: Libya can lead the world in renewable energy. It has a very high daily solar radiation rate. Section II. Libya's strategy for transitioning to a green hydrogen economy. Section III. Ttypes hydrogen production colors. Section IV. Presents routes for the production of green hydrogen production. Section V. Hydrogen storage prospects in Libya. Section VI. Libyan economic costs of electricity production from hydrogen. Section VII. Green hydrogen utilization techniques. Section VIII. Finally, the cost of producing hydrogen. A summary of the conclusion followed by the references closing the article.

2. LIBYA'S STRATEGY FOR TRANSITIONING TO A GREEN HYDROGEN ECONOMY

Libya faces several obstacles as it begins to establish a green hydrogen economy. Considering the possibility of production and various routes of use, in addition to its goal of achieving net-zero emissions by 2050 and a 75% reduction in emissions by 2030, a series of steps can be taken to move the economy toward green hydrogen. For green hydrogen to be produced on a big scale using renewable energy sources, there must first be a market for it. According to Fig. 3, green hydrogen is predicted to enter Libyan in three stages. Involves leveraging its abundant solar and wind resources to produce renewable hydrogen. The country aims to invest in large-scale renewable energy projects and develop the necessary infrastructure to support the production, storage, and distribution of green hydrogen. This transition will not only reduce Libya's dependence on fossil fuels but also create new economic opportunities and drive sustainable development. With a clear roadmap and strong commitment from the government, Libya is poised to become a key player in the global green hydrogen market [17-22].

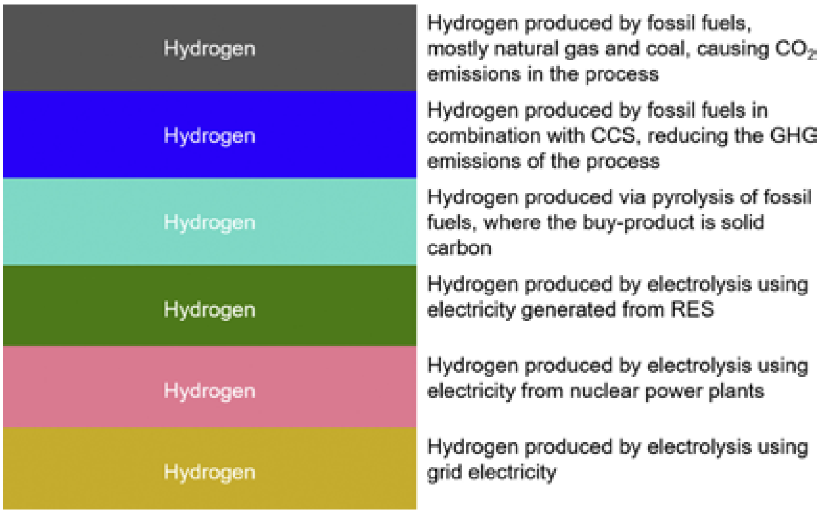

Fig. 3. Charging techniques for various stages [23].

3. TYPES OF HYDROGEN PRODUCTION COLORS

Three primary categories can be distinguished between hydrogen generations based on the source material:

i. Hydrogen generation from hydrocarbons, such as biomass, and fossil fuels like coal, oil, and natural gas.

ii. Direct water splitting, which produces hydrogen.

iii. Direct reactions between chemical reagents, such as metals, acids, and bases, produce hydrogen.

Each of these categories has its own set of advantages and challenges, and ongoing research and development is focused on improving the efficiency, cost-effectiveness, and environmental impact of each hydrogen generation technology. There are several major energy sources from which hydrogen can be created. The cost of producing hydrogen and its associated emissions can vary greatly depending on the type of energy utilized. This is the reason why various colors such as grey, blue, turquoise, green, purple, and yellow are frequently used to categorize hydrogen-generating systems see Fig. 4.

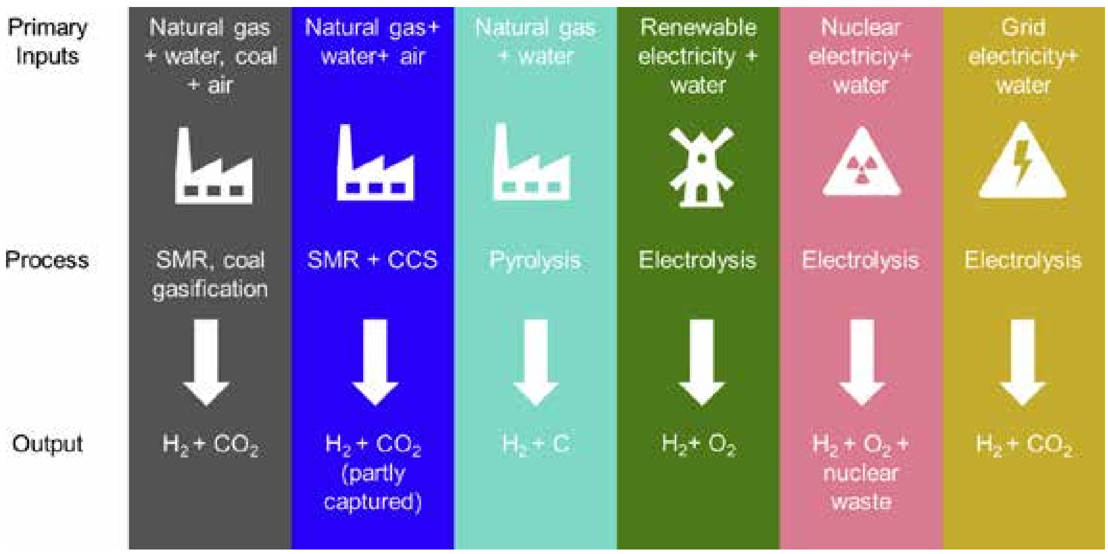

Fig. 4. Several colors of producing hydrogen [34].

Fig.5 provides an overview of all the ways to produce hydrogen that have been mentioned. Several colors produce hydrogen. we refer to all methods of producing hydrogen that rely on fossil fuel inputs without the use of carbon capture and storage as grey hydrogen for this analysis, as is the case with the majority of scientific literature. Grey hydrogen is currently the most widely used form of hydrogen production, but it comes with significant environmental drawbacks due to its carbon emissions. As the world seeks to transition to a more sustainable energy system, there is a growing focus on developing and scaling up cleaner forms of hydrogen production, such as green and blue hydrogen [24].

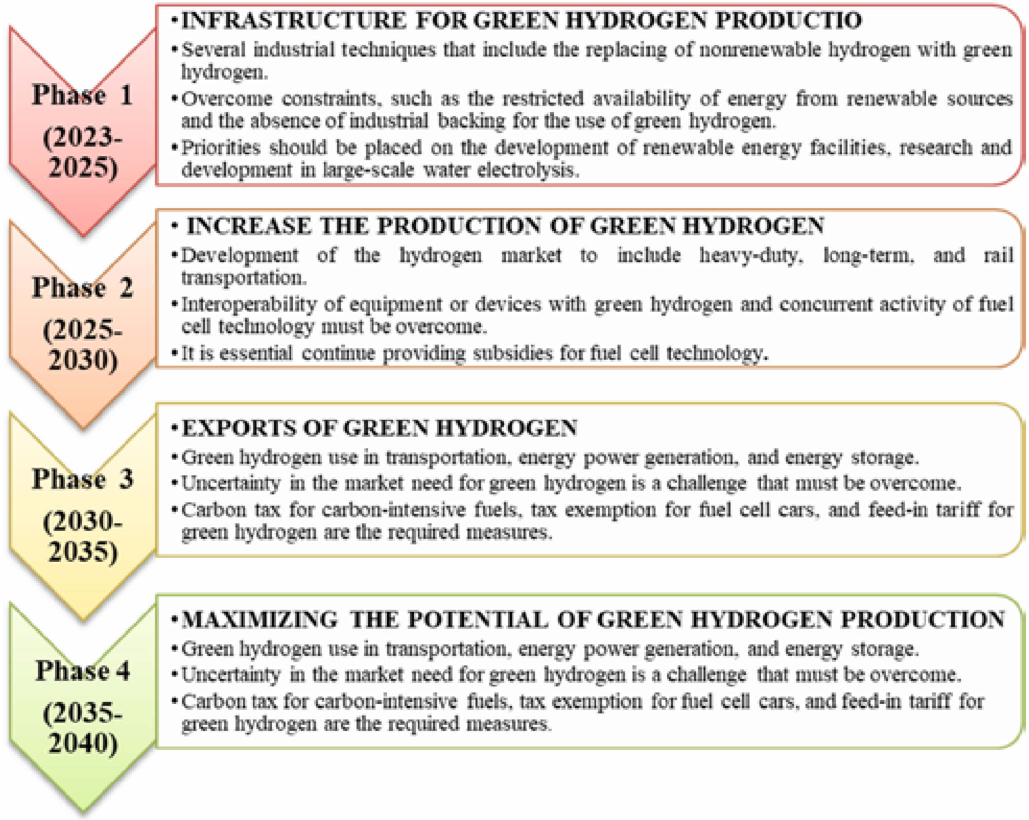

Fig. 5 Overview of all the ways for producing hydrogen [34].

Using Libya's natural gas to produce gray hydrogen has a major drawback in the form of substantial carbon dioxide emissions during the hydrogen generation process. However, natural gas steam reforming without CCUS is a proven, cost-effective method for hydrogen production. Water is heated, and natural gas is pretreated.

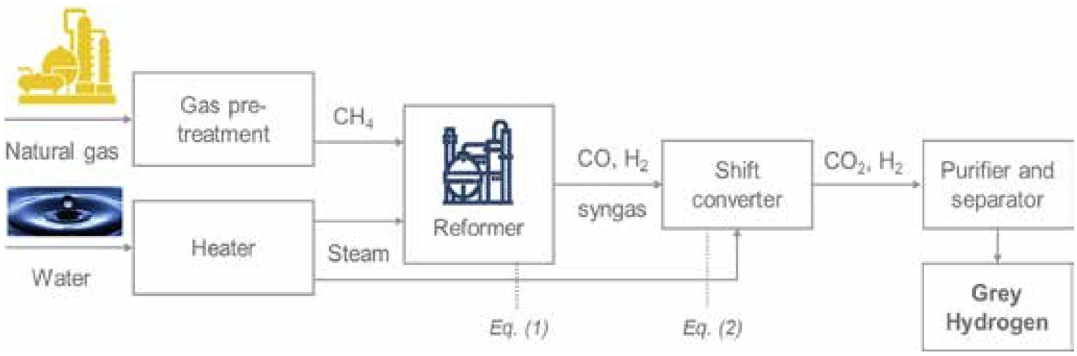

Fig. 6. Using Libya's natural gas to produce gray hydrogen [34].

The methane is then broken down into syngas in the reformer using steam, with the primary

constituents being CO and H_2. Subsequently, this is converted into CO_2 and H_2 through the water gas shift reaction, with the CO_2 being separated and the H_2 being purified as shown in Fig.6.
Natural gas steam reforming is a widely used method for industrial hydrogen production due to its efficiency and cost-effectiveness. However, substantial carbon dioxide emissions associated with this process pose a significant environmental challenge.
Implementing carbon capture, utilization, and technologies could mitigate these emissions, making gray hydrogen production more sustainable. In addition, exploring alternative methods such as green hydrogen production from renewable sources could further reduce the environmental impact of hydrogen generation [25].

4. ROUTES FOR THE PRODUCTION OF GREEN HYDROGEN

Green hydrogen There are several potential pathways for the production of green hydrogen in Libya, including electrolysis powered by renewable energy sources such as solar and wind power, as well as biomass gasification. These methods offer promising opportunities for Libya to diversify its energy resources and reduce its carbon footprint. With its abundant renewable energy potential and strategic geographical location, Libya has the potential to become a key player in the global green hydrogen market. Libya's commitment to green hydrogen production aligns with global efforts to transition towards sustainable and low-carbon energy sources. By leveraging its natural resources and investing in renewable energy infrastructure, Libya can position itself as a leader in the green hydrogen sector, contributing to both its economic growth and environmental sustainability. In Fig .7 possible pathways for green hydrogen production in Libya provide various opportunities for producing green hydrogen. With its abundant sunlight and vast desert landscapes, Libya is well-suited for large-scale solar power projects that can be used to produce green hydrogen. Additionally, the country has access to ample water resources along its coastline, which can be used in the electrolysis process to split water into hydrogen and oxygen. These factors make Libya a prime location for harnessing the potential of green hydrogen as a clean and sustainable energy source.

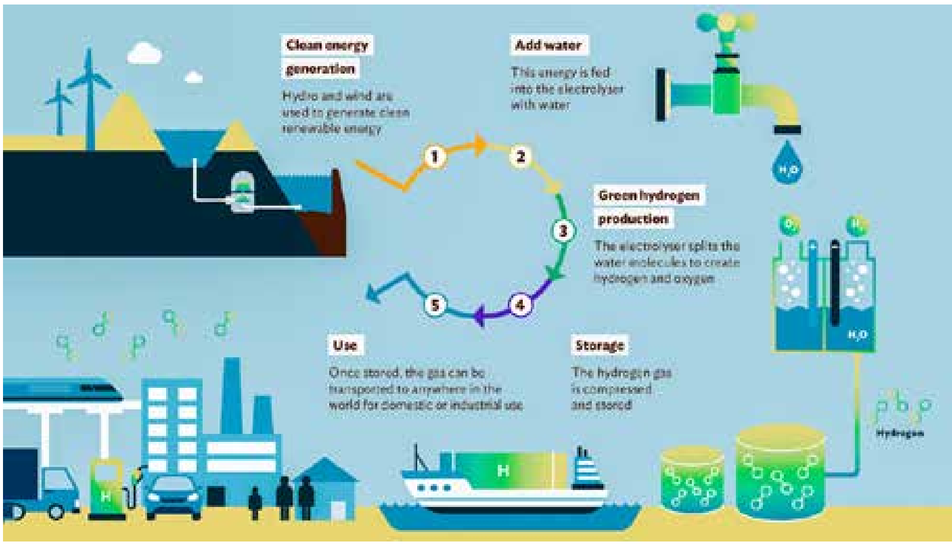

Fig 7. Potential routes for Libya's generation of green hydrogen [26].

Green hydrogen is produced by using electricity from renewable energy sources to electrolyze water. This type of hydrogen is receiving special attention as we transition to a more environmentally friendly energy and transportation system. Terms such as "clean hydrogen," "renewable hydrogen," or "low-carbon hydrogen" are also used to describe green hydrogen in literature. Green hydrogen can potentially play a significant role in reducing carbon emissions and addressing climate change. It can be used as a clean fuel for transportation, heating, and industrial processes, offering a sustainable alternative to fossil fuels. As the demand for green hydrogen continues to grow, efforts to scale up production and reduce costs are underway, making it an increasingly viable option for a greener future. In Fig.8. shows the general schematic electrolysis process. Liquid electrolyze solutions can be used for electrolytes.

The function at higher temperatures functions by transmitting electricity through the water, which produces positively charged hydrogen ions at the anode together with oxygen. Hydrogen gas is created when this passes through the liquid electrolytes and combines with the electrons from the external circuit. when there is a solid electrolyte. At the cathode, the water dissociates and combines with electrons from the external circuit to form H_2 and negatively charged O2. Oxygen gas is produced when O2 diffuses through the membrane and releases electrons at the anode [27].

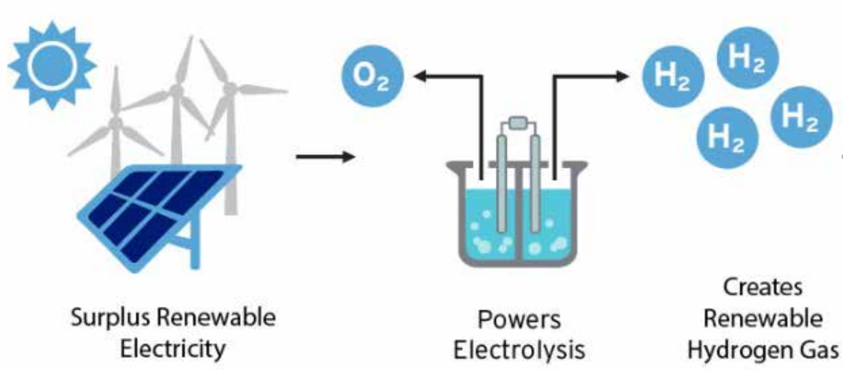

Fig. 8 General schematic electrolysis process [41].

Because of its great energy conversion and extremely low emission levels, hydropower is another renewable energy source that has the best ecological efficiency. There are three main types of hydropower plants: run-of-river plants, whose generation depends on the reservoir plants, which can store a significant amount of water behind the dam and effectively function as an electrical storage system; river flows, which depend on the time and volume of flows since they have little to no storage capacity behind the dam; and pumped storage systems, which draw water from a reservoir utilizing off-peak electricity. Hydropower is an incredibly versatile source of renewable energy that can be used to generate electricity on a large scale [28-29].

Numerous research works have examined the techno-economic aspects of producing green hydrogen from potential hydropower excess energy in various nations. The predominant renewable energy sources are hydropower and geothermal energy. Because there is a surplus of water in the nation, extra water is diverted toward the spillway, which can result in flooding, landslides, and erosion, particularly during the rainy seasons. Green hydrogen can be produced during high-throughput seasons using extra energy and water, potentially alleviating energy shortages [30].

Offshore wind power aims to maximize energy efficiency and reduce waste by utilizing excess wind power to produce hydrogen and liquefy gaseous hydrogen using cold energy. This innovative approach allows for the storage and transportation of hydrogen, providing a sustainable energy solution for various applications. Fig.9 displays the offshore wind configuration in its entirety. The offshore wind power project integrates cutting-edge technology to harness renewable energy sources and address the growing demand for clean energy. By leveraging excess wind power to produce and store hydrogen, the project offers a viable solution for energy storage and transportation. This sustainable approach not only reduces waste but also contributes to the overall efficiency of the energy system [31].

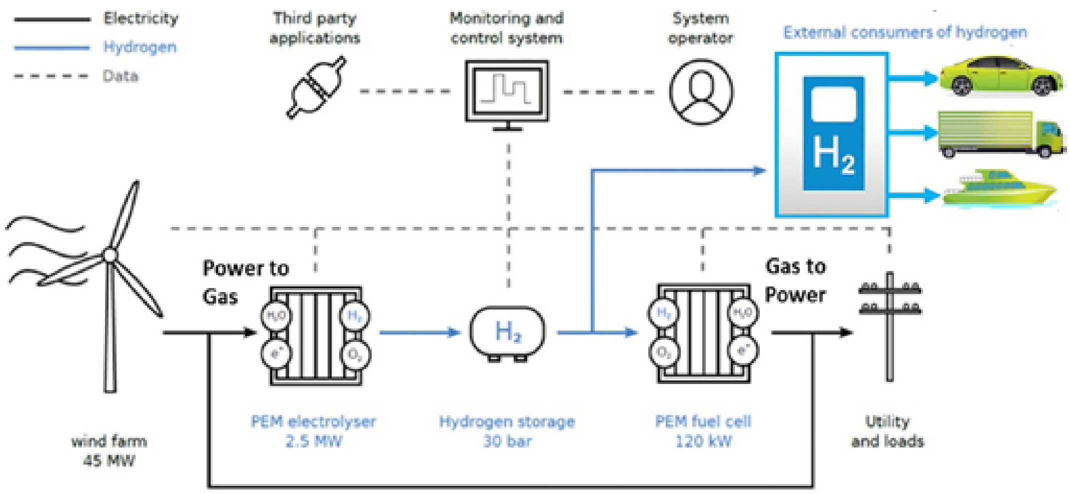

Fig.9 displays the offshore wind configuration in its entirety [34].

Green hydrogen is non-polluting and favorable to the environment, the most promising, efficient, and clean energy source. The generation of green hydrogen from solar energy has promise for meeting the global need for sustainable green energy, supplanting finite fossil fuels, and mitigating climate change caused by carbon dioxide emissions. Photocatalytic water splitting is a necessary and beneficial process that converts renewable, sustainable solar energy into hydrogen. Nevertheless, the efficacy of photocatalytic water splitting is dependent on opsonic and chemical features. If capital costs drop considerably, hydrogen production from renewable energy sources could eventually become viable (2030–2050). Minimum production costs for hydrogen from renewable energy sources should drop to less than $1/kg in some places with optimistic assumptions and to $1.5/kg under central assumptions by 2050. The most economical long-term source of hydrogen is contingent upon regional factors, including gas pricing and the possibility of renewable energy. Hydrogen imports from renewable energy sources are more economical when there is limited or high domestic production potential. The development of advanced photocatalysts and efficient solar energy conversion systems is crucial to overcoming the current limitations and maximizing the potential of solar hydrogen energy. Furthermore, in Fig. 10 green hydrogen production from solar and wind energy novel research in material science and nanotechnology is driving the exploration of innovative photocatalytic materials and nanostructures, aiming to enhance light absorption, charge separation, and surface reactivity. These advancements are pivotal in improving the overall efficiency of solar hydrogen production. Additionally, the integration of advanced reactor designs and engineering solutions holds significant promise in scaling up the production of green hydrogen from solar energy, making it a viable and competitive energy source for the future [32].
Although there are potential financial and environmental advantages to green hydrogen, there are also financial and technological obstacles that must be removed before it can be widely used. Over time, opportunities can be realized and hazards can be mitigated with coordinated policy support and scientific research and development.

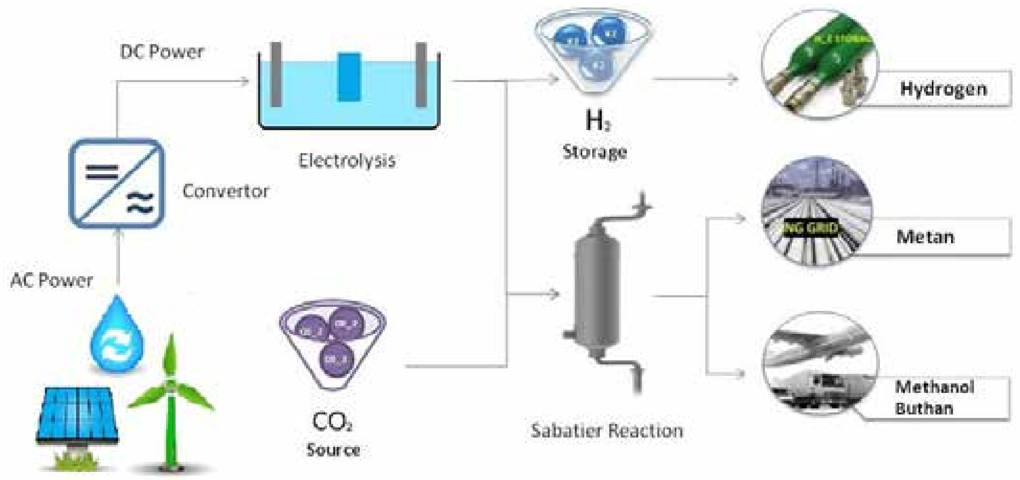

Fig.10 Green hydrogen production from solar and wind energy [34].

It is essential to address these challenges through collaborative efforts to unlock the full potential of green hydrogen as a sustainable energy solution. By fostering innovation and investment in infrastructure, as well as promoting international cooperation, we can pave the way for a more efficient and cost-effective green hydrogen industry. This will not only contribute to a cleaner and greener future but also create new economic opportunities and drive global progress towards a low-carbon economy. in TABLE III SWOT analysis of the production of green hydrogen [35].

TABLE III. SWOT analysis of the production of green hydrogen.

Strengths	Weaknesses	Opportunities	Threats
A sustainable and renewable energy source that emits no greenhouse gases	At the moment, producing hydrogen from fossil fuels is more costly.	Possibility of expanding as renewable energy technologies develop and costs come down.	Price competitiveness is hampered by hydrogen from fossil fuels' ongoing cheap cost.
The possibility of decarbonizing challenging industries to electrify, such as transportation and heavy industry.	Lack of infrastructure and immature technologies prevent large-scale production and distribution.	Increasingly, energy-intensive businesses are seeking low-carbon alternatives.	In certain applications, hydrogen might be replaced by other low-carbon technology, such as batteries.
Capacity to distribute and store renewable energy over great distances and promptly.	Production facilities and distribution networks have high initial capital costs.	Growth of global markets and commerce for hydrogen Possibilities for economic expansion, job development in the hydrogen industry	Issues with public acceptance of production, storage, and transportation safety.
Increasing global government support for investments and policies.	The availability of renewable energy sources, such as solar and wind power, determines production.	Possibility for a strategic alliance with nations or areas rich in renewable energy.	Geopolitical concerns regarding dependence on imports of essential minerals and materials.

5. HYDROGEN STORAGE PROSPECTS IN LIBYA

Libya has oil and gas it can generate gray hydrogen but finding suitable storage locations for the captured carbon that cannot be used is another issue. There are situations where storing carbon underground may need high upfront costs. The overall cost of hydrogen may be substantially more than that of gray hydrogen because of CCUS. Furthermore, who is responsible for the CO_2 and the expense of storage is not yet controlled [22]. The entire procedure and necessary steps are shown in Fig.11 Finding the right balance between cost-effective storage options and environmental impact is crucial in the development of carbon capture and storage technology. In addition, the potential risks associated with underground storage, such as leakage and seismic activity, must be carefully assessed and managed.

It is clear that there are still many challenges to overcome in the implementation of large-scale carbon capture and storage, but continued research and innovation in this area are essential for addressing the urgent issue of climate change [32].

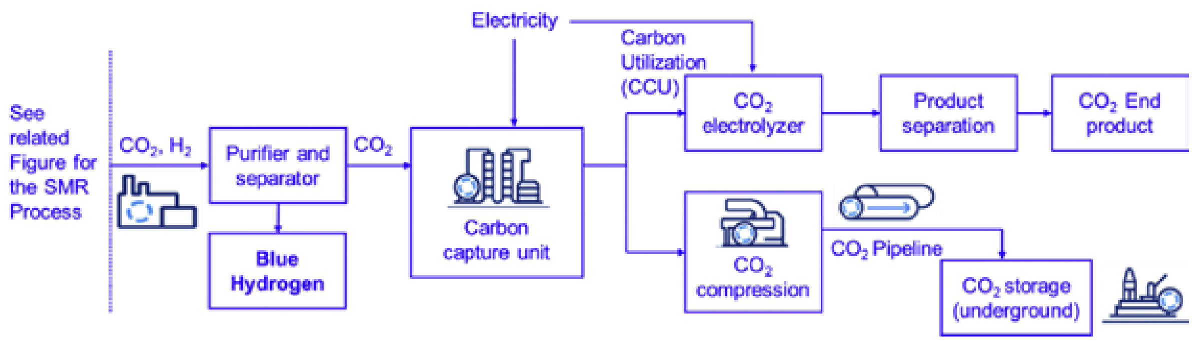

Fig.11 Producing gray hydrogen for carbon capture method [34].

6. LIBYAN ECONOMIC COSTS OF ELECTRICITY PRODUCTION FROM HYDROGEN

One of the primary reasons for the reluctance to adopt this process is the high economic costs involved. Manufacturers are striving to minimize project costs, whether they pertain to investment, maintenance, or construction. Nevertheless, the expenses remain relatively high compared to other methods of electricity production. In Table (IV), the cost in Libyan dinar per kg of hydrogen is presented, showing considerable improvement. While this cost is undoubtedly significant, over time, production costs are decreasing. Despite the initial high costs, advancements in technology and economies of scale are steadily driving down the expenses associated with hydrogen-based electricity production. This trend is expected to continue, making it a more viable and competitive option in the future.

As research and development efforts progress, it is anticipated that the cost of hydrogen production and subsequent electricity generation will further decrease, making it a more attractive and sustainable energy solution for Libya.

TABLE IV. Hydrogen type with cost in Libyan dinar per kg.

No.	Hydrogen Type	Cost (dinar per kg)
1	Green (Renewable Energy)	15 - 38
2	Gray (Natural Gas)	4.5 – 16
3	Blue (with Carbon Capture, Storage, and Utilization Techniques	7.5 – 14.5

7. GREEN HYDROGEN UTILIZATION TECHNIQUES

Libya's government's initiative for zero emissions presents an opportunity for the expansion of the green hydrogen economy and renewable energy sources. As per the country's Energy Policies 2023 and 2035, green hydrogen can be utilized in the following ways. Green hydrogen can be utilized in the following ways: as a clean fuel for transportation, as a means to store and transport renewable energy, and as a feedstock for industrial processes such as ammonia production.

These initiatives align with global efforts to reduce carbon emissions and combat climate change. By leveraging its abundant solar and wind resources, Libya can position itself as a key player in the emerging green hydrogen market, contributing to both environmental sustainability and economic growth. The majority of governmental initiatives have concentrated on road transportation, specifically on fuel-cell electric cars and recharging facilities. As a result of the increased emphasis on a wider range of hydrogen uses, national strategies, infrastructure, supply, and industrial acceptance are receiving more attention from policymakers. This shift in focus is a positive step towards promoting the adoption of hydrogen technology across various sectors. By addressing infrastructure and supply challenges, Libyan governments can create an environment that encourages the widespread use of hydrogen in transportation, industry, and energy production. This holistic approach will ultimately contribute to reducing greenhouse gas emissions and advancing the transition toward a more sustainable and low-carbon economy. Hydrogen utilization techniques in fuel cell automobiles Although hydrogen is primarily utilized as a chemical compound today, it has other important uses the primary use is to store excess electricity produced by renewable sources, either to convert it back into electricity (with very high losses) or for use in industrial processes, natural gas grid injection, or fuel cell vehicles for transportation as shown in Fig. 12. Fuel cell vehicles are a promising technology that can help reduce greenhouse gas emissions from transportation. These vehicles use hydrogen as fuel and emit only water vapor as a byproduct, making them a clean alternative to traditional gasoline-powered vehicles. However, the widespread adoption of fuel cell vehicles is currently limited by the high cost of production and the lack of infrastructure for hydrogen refueling. Despite these challenges, many automakers are investing in the development of fuel-cell vehicles, and governments around the world are providing incentives to encourage their adoption [33].

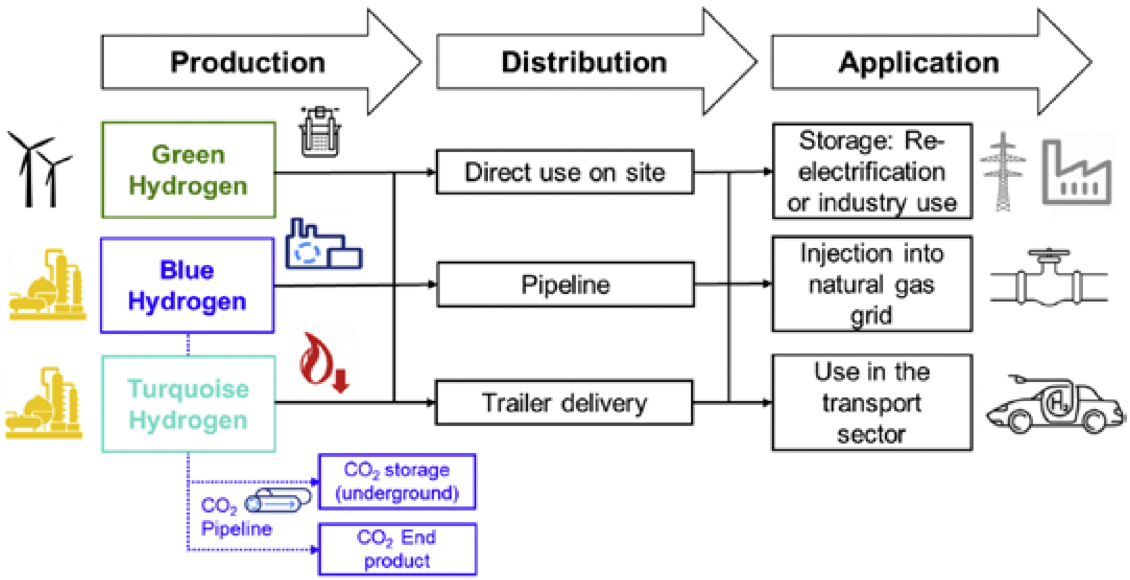

Fig. 12. Hydrogen utilization techniques [34].

8. COST OF PRODUCING HYDROGEN

Energy requirements (kWh/kg H_2) Electrolysis 39 kWh/kg H_2 is the theoretical minimum energy needed for water electrolysis. Since commercial alkaline electrolyzers typically have an efficiency of roughly 70%, the energy needed is more in the range of 55–60 kWh/kg H_2. Renewable energy input depends on the renewable source's capacity factor, a certain quantity of renewable energy input is needed. For instance, 180 kWh of renewable energy would be required for every kilogram of hydrogen produced (55 kWh/kg H_2 / 0.3 capacity factor) if the renewable source had a 30% capacity factor. Production cost ($/kg H_2) capital costs include the electrolyzer system, storage, compression, and the production of renewable energy from solar and wind turbines, among other sources. Spread out over a lifetime. Levelized cost of electricity from renewable sources expressed in dollars per kilowatt-hour. Multiplied by the amount of energy needed in kWh/kg H_2.The levelized cost of electricity from renewable sources is a crucial factor in determining the overall production cost of hydrogen. By multiplying the amount of energy needed in kWh/kg H_2 by the levelized cost of electricity, we can gain insight into the financial implications of hydrogen production. This approach allows for a comprehensive understanding of the economic viability of utilizing renewable energy sources for hydrogen generation. O&M Costs: Includes operating and maintenance costs for the system over a lifetime. The transport/Distribution cost of transporting hydrogen to the point of use, includes compression, storage, etc. if applicable. Other: Costs like land, permitting, etc. Total levelized cost: add up capital costs amortized, electricity costs, O&M, transport over lifetime kg of hydrogen produced. Divide by lifetime kg of H_2 to get $/kg. The key is using realistic assumptions around utilization rates, lifetimes, and financing to get an accurate total levelized cost of production. This methodology allows comparison to other production methods [36], [37]. Based on average fossil fuel costs over the long run of Dinar Libyan LYD 375/bbl for oil and LYD 20-30/GJ for natural gas, the cost of producing renewable hydrogen is two to three times higher than that of fossil references. Pipelines for hydrogen may be 10–50% more expensive. When it comes to road transportation, fuel cells and storage tanks are far more costly than internal combustion engines. Currently, jet fuel derived from fossil oil can be three to six times more expensive than synthetic fuel for flight. For ammonia, methanol, and steel, the cost premium for renewable paths over fossil fuel-based alternatives can range from 50–75%, 150%, and 30–40%, respectively. However, it is important to note that while renewable energy sources may have a higher initial cost, they have the potential to provide significant long-term cost savings and environmental benefits. As technology continues to advance and economies of scale are achieved, the cost of producing renewable hydrogen, fuel cells, and storage tanks is likely to decrease. Additionally, the cost of fossil fuels may increase due to supply and demand fluctuations, geopolitical tensions, and environmental regulations. Therefore, the Libyan government's investing in renewable energy sources may prove to be a wise financial decision in the long run. Right now, there is no price index for the sale of hydrogen because it is not a traded commodity. Customers will pay more as a result of the lack of price transparency and competition. Low-carbon hydrogen is not in high demand, so initiatives must be integrated from supply to infrastructure and end-use. This lack of demand can also be attributed to the high cost of producing low-carbon hydrogen, as well as the limited infrastructure for its distribution and use. Without a clear price index and competitive market, the adoption of low-carbon hydrogen will continue to face significant barriers. Initiatives to drive down costs and increase demand for low-carbon hydrogen will be crucial in unlocking its potential as a clean energy source [38].

The production, processing, and transportation of hydrogen or the extraction, processing, and delivery of fuels (coal, natural gas) are examples of upstream and midstream emissions. These emissions also encompass CO_2 and methane emissions. The impact of today's observed range of upstream and midstream emissions on emissions intensity is shown by error bars for coal and natural gas. The lowest bound for natural gas stands at 4.5 kg CO_2-eq/GJ, reflecting the current best available technology; the upper limit is 28 kg CO_2-eq/GJ, representing the 95th percentile of the global range. For coal, the lower limit corresponds to the 5th percentile (6 kg CO_2-eq/GJ), while the upper limit matches the 95th percentile (23 kg CO_2-eq/GJ) of the upstream and midstream emissions of coal supply worldwide. The generation-weighted global average of grid power intensity serves as the basis for the 2021 world grid average. The error bars show the 10% percentile (50 g CO_2-eq/kWh) and 90% percentile (700 g CO_2-eq/kWh) for each country. The power stations' direct emissions of CO_2, CH4, and N2O are included in the grid electricity intensity; however, the upstream and midstream emissions of the fuels utilized in the power plants are not. The embedded emissions that result from the manufacturing of solar PV systems (27 g CO_2-eq/kWh) and onshore wind turbines (12 g CO_2-eq/kWh) are referred to as dashed lines.

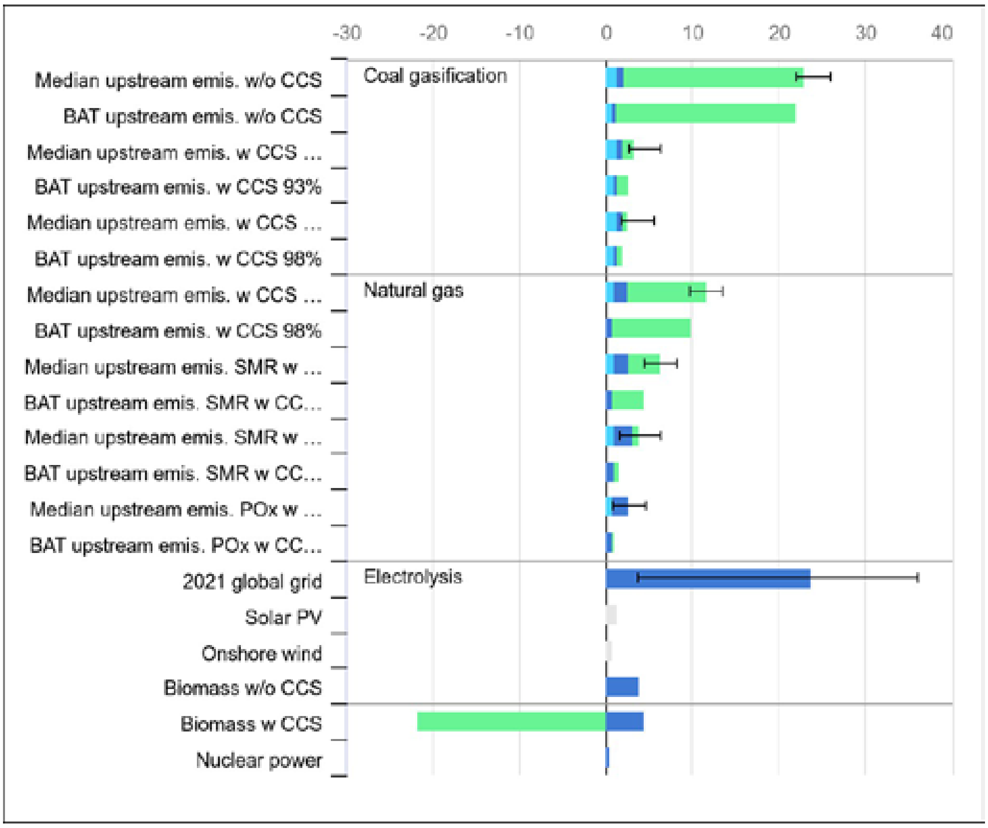

Fig. 13. Emission intensity comparison of various hydrogen production routes [39].

These embedded emissions are shown here primarily for demonstrative purposes and are not part of the IPHE methodology. Low-temperature water electrolysis is referred to as electrolysis, and an overall electricity consumption of 50 kWh/kg H_2 is anticipated, including compression to 30 bar. If there is no CO_2 collection, the production of hydrogen from natural gas by SMR is based on 44.5 kWh/kg H_2, on 45.0 kWh/kg H_2, in the case of a 60% capture rate, and on 49 kWh/kg H_2 for natural gas and 0.8 kWh/kg H_2 for electricity in the case of a 93% capture rate. The demands of 41 kWh/kg H_2 for natural gas and 0.6 kWh/kg H_2 for electricity, assuming a 99% capture rate, are the basis for the hydrogen synthesis from natural gas using POx. Gasification is used to produce hydrogen from coal, and it requires 57 kWh of coal for every kilogram of H_2 and 0.7 kWh of electricity for every kilogram of H_2. 59 kWh/kg H_2 of coal is required for a 93% CO_2 capture rate in the absence of CO_2 collection, while 60 kWh/kg H_2 of coal is required for a

98% CO_2 capture rate. As shown in Fig. 13. Emission intensity comparison of various hydrogen production routes. The BAT = best available technology; CCS = carbon capture and storage; SMR = steam methane reforming; POx = partial oxidation; Median upstr. emis. = global median value of upstream and midstream emissions in 2021; BAT upstr. emis. = best available technology today to address upstream and midstream emissions. Colors in the next figure show that baby blue represents upstream and midstream emissions - methane. The blue represents upstream and midstream emissions - CO_2. The green represents direct emissions. [39].

9. CONCLUSIONS

The hydrogen industry is expanding as a result of rising climate change concerns and technological advancements. Globally, corporations and governments are investing in hydrogen technology and infrastructure to replace fossil fuels like diesel with hydrogen soon. Libya has great potential for producing green hydrogen due to its abundance of renewable energy sources, including wind, and, despite being in the early stages of development. Green hydrogen can potentially reduce energy consumption in various sectors such as the built environment, transportation, industry, and utilities. Libya's economy still faces technological and economic obstacles because it is dependent on gas and oil. To overcome these challenges and advance the country's hydrogen economy and renewable energy sources, the government can play a significant role. For Libya to become a renewable energy and green hydrogen economy by 2050, the country's energy industry must be entirely renewable. To achieve this, Libya can focus on investing in solar and wind energy infrastructure, as well as developing the necessary technology for green hydrogen production. Additionally, the government can work on creating a favorable regulatory environment and attracting foreign investment to support the transition to renewable energy.

Author Contributions: The idea and design of the study were contributed to by all authors. When it comes to preparing materials, gathering data, and analyzing it, all authors are equal. The first draft of the manuscript was written by (Ibrahim Imbayah) and (Mashhood Hasan). After reading the published version of the manuscript, all authors have given their approval.
Funding: "There is no fund received for this work".
Data Availability Statement: "The data are available at request".
Acknowledgments: "The authors would like to express their appreciation for all the support from the College of Renewable Energy, Tajoura, Libya (CRE-T) for their support".
Conflicts of Interest: "The authors declare that there is no conflict of interest".

REFERENCES

[1] Y. Fathi, H. El-Khozondar, W. El-Osta, S. Mohammed, M. Elnaggar, M. Khaleel, A. Ahmed, A. Alsharif, Carbon footprint and energy life cycle assessment of wind energy industry in Libya, Energy conversion and management, vol. 300, 15 January 2024, 117846, https://doi.org/10.1016/j.enconman.2023.117846.

[2] N. Yasser, H. El-Khozondar, G. Ghaboun, M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, 2023. Solar and wind atlas for Libya, International Journal of Electrical Engineering and Sustainability (IJEES), vol. 1, no. 3, pp. 27-43. https://ijees.org/index.php/ijees/article/view/44/20.

[3] A. Maka and J. Alabid, "Solar energy technology and its roles in sustainable development," Clean Energy, vol. 6, no. 3, pp. 476–483, Jun. 2022, doi: 10.1093/ce/zkac023.

[4] L. Rtemi, W. El-Osta, A. Attaiep, Hybrid system modeling for renewable energy sources, Journal of Solar Energy and Sustainable Development, vol. 12, no. 1, pp. 13-28.

[5] M. Almihat, M. Kahn, Design and implementation of Hybrid Renewable energy (PV/Wind/ Diesel/Battery) Microgrids for rural areas, Journal of Solar Energy and Sustainable Development, vol. 12, no. 1, pp. 80–104.

[6] S. Mohammed, Y. Nassar, W. El-Osta, H. El-Khozondar, A. Miskeen, and A. Basha, "Carbon and Energy Life Cycle Analysis of Wind Energy Industry in Libya," Solar Energy and Sustainable Development Journal, vol. 12, no. 1, pp. 50–69, 2023.

[7] Y. Nassar, H. El-Khozondar, N. Abohamoud, A. Abubaker, A. Ahmed, A. Alsharif, M. Khaleel, 2023. Regression Model for Optimum Solar Collectors' Tilt Angles in Libya. The 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES 2023), May 8-9, 2023, Gaza Strip, Palestine, pp. 1-6.

[8] I. Imbayah, A. Ahmed, A. Alsharif, M. Khaleel, A. Alarga, "A Review of the Possibility Integrating the Solar System into the Libyan Railway Transportation". African Journal of Advanced Pure and Applied Sciences (AJAPAS), Volume 2, Issue 2, April-June 2023, Page No: 1-10.

[9] https://cleantechnica.com/2013/06/29/libya-solar-potential-5x-larger-than-oil-reserves-infographic/.

[10] L. Dogaru "The main goals of the Fourth Industrial Revolution. Renewable energy perspectives". Procedia Manuf, 46 (2020), pp. 397-401, doi. 10.1016/j.promfg.2020.03.058.

[11] J.A. Duro, C. Lauk, T. Kastner, K.-H. Erb, H. Haberl "Global inequalities in food consumption, cropland demand, and land-use efficiency: A decomposition analysis". Glob Environ Chang, 64 (2020), Article 102124, 10.1016/j.gloenvcha.2020.102124.

[12] D.A. Hutchins, J.K. Jansson, J.V. Remais, V.I. Rich, B.K. Singh, P. Trivedi "Climate change microbiology — problems and perspectives". Nat Rev Microbiol, 17 (6) (2019), pp. 391-396, 10.1038/s41579-019-0178-5.

[13] A. Rahman, O. Farrok, M.M. Haque."Environmental impact of renewable energy source-based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic". Renew Sustain Energy Rev, 161 (2022), Article 112279, doi:10.1016/j.rser.2022.112279.

[14] R. Hren, A. Vujanović, Y. Van Fan, J.J. Klemeš, D. Krajnc, L. Čuček. "Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment". Renew Sustain Energy Rev, 173 (2023), doi:10.1016/j.rser.2022.113113.

[15] M. Almaktar, A. M. Elbreki, and M. Shaaban, "Revitalizing operational reliability of the electrical energy system in Libya: Feasibility analysis of solar generation in local communities," J. Clean. Prod., vol. 279, p. 123647, 2021, doi: 10.1016/j.jclepro.2020.123647.

[16] A. Miskeen, R. Elzer, I. Mangir,Y. Nassar, H. ElKhozondar, M. Khaleel, A. Ahmed, A. Alsharif, I. Imbayah. "Electricity from Wastewater Treatment Plants", Solar Energy And Sustainable Development. 2023, pp.24–37.

[17] M. Fawzi, T. Hamad, and A. Azouz, "Hazard and Economical Evaluation for a Hydrogen Fuel Station", jsesd, vol. 9, no. 2, pp. 1–10, Dec. 2020.

[18] M. Ashur, "An Integrated System of Gasoline Reformer and Thee Way Converter for On-board Hydrogen Production", jsesd, vol. 2, no. 1, pp. 38–47, Dec. 2013.

[19] I. Mohamed, "Solar Hydrogen System Configuration Using Genetic Algorithms", jsesd, vol. 1, no. 1, pp. 18–24, Jun. 2012.

[20] H. Ahmed and A. Musa, "Performance Parameters of Direct Coupling Advanced Alkaline Electrolysis and PEMFC System", jsesd, vol. 9, no. 2, pp. 29–45, Dec. 2020.

[21] A. Kagilik, "Dry Phosphorus silicate glass etching and surface conditioning and cleaning for multi-crystalline silicon solar cell processing" " Jsesd, vol. 3, no. 1, pp. 38–50, Dec. 2014.

[22] A. Musa, R. Arfa, and A. Agina, "Optimal Operating Point of a Hydrogen Fueled SOFC Models Using Al-Nour Software", jsesd, vol. 5, no. 2, pp. 1–9, Dec. 2016.

[23] Hassan, Q., Sameen, A. Z., Salman, H. M., Jaszczur, M., Al-Hitmi, M., & Alghoul, M. "Energy futures and green hydrogen production: Is Saudi Arabia trend? Results in Engineering", (2023). https://doi.org/10.1016/j.rineng.2023.101165.

[24] M. Newborough, G. Cooley." Developments in the global hydrogen market:the spectrum of hydrogen colors," Fuel Cell Bull, 2020 (11) (2020), pp. 16-22, 10.1016/S1464-2859(20)30546-0.

[25] A. Mostafaeipour, S.J. Hosseini Dehshiri, S.S. Hosseini Dehshiri, "Ranking locations for producing hydrogen using geothermal energy in Afghanistan," Int J Hydrogen Energy, 45 (2020), pp. 15924-15940, 10.1016/j.ijhydene.2020.04.079.

[26] Ratnakar RR, Gupta N, Zhang K, van Doorne C, Fesmire J, Dindoruk B, et al. "Hydrogen supply chain and challenges in large scale LH2 storage and transportation". Int J Hydrogen Energy 2021. doi.org/10.1016/ j.ijhydene.2021.05.025.

[27] Y.E. Yuksel, M. Ozturk, "Thermodynamic and thermoeconomic analyses of a geothermal energy based integrated system for hydrogen production,". Int J Hydrogen Energy, 42 (2017), pp. 2530-2546, 10.1016/j.ijhydene.2016.04.172.

[28] Y.E. Yuksel, M. Ozturk, I. Dincer, "Evaluation of a new geothermal based multigenerational plant with primary outputs of hydrogen and ammonia". Int J Hydrogen Energy, 46 (2021), pp. 16344-16359, 10.1016/j.ijhydene.2020.12.144.

[29] S.M. Alirahmi, E. Assareh, N.N. Pourghassab, M. Delpisheh, L. Barelli, A. Baldinelli, "Green hydrogen & electricity production via geothermal-driven multi-generation system: thermodynamic modeling and optimization". Fuel, 308 (2022), 10.1016/j.fuel .2021.122049, doi: 10.1016/j.pecs.2019.04.002.

[30] Chen, X., Yue, J., Fu, L., Zhang, M., Tang, M., Feng, J., & Shen, B. (2023). "Green hydrogen production and liquefaction using offshore wind power, liquid air, and LNG cold energy". Journal of Cleaner Production, 423. doi: /10.1016/j.jclepro.2023.138653.

[31] Ponnala Rambabu, Nageswara Rao Peela, "In-situ CdS nanowires on g-C3N4 nanosheet heterojunction construction in 3D-Optofluidic microreactor for the photocatalytic green hydrogen production," International Journal of Hydrogen Energy, 2023, pp. 15406-15420, doi.org/10.1016/j.ijhydene.2023.01.041.

[32] M. Amin, E. Croiset, W. Epling, "Review of methane catalytic cracking for hydrogen production," Int J Hydrogen Energy, 36 (4) (2011), pp. 2904-2935, 10.1016/j.ijhydene.2010.11.035.

[33] Alexander Körner, "Technology Roadmap Hydrogen and Fuel Cells," Technical Annex. pp.1-29. Jun-2015.

[34] Ajanovic, A., Sayer, M., & Haas, R. " The economics and the environmental benignity of different colors of hydrogen". International Journal of Hydrogen Energy, (2022). 47(57), 24136–24154. doi.org/10.1016/j.ijhydene.2022.02.094.

[35] Muhammad, K. Sami ,G. " Hydrogen economy for sustainable development in GCC countries: A SWOT analysis considering the current situation, challenges, and prospects". International Journal of Hydrogen Energy Volume 48, Issue 28, 1 April 2023, Pages 10315-10344. https://doi.org/10.1016/j.ijhydene.2022.12.033.

[36] Ivanenko, N. P. and Petr Vladimirovich Tarasenko. "Cost of hydrogen production with using the share of electricity from a wind power plant in Ukraine." The Problems of General Energy (2021), pp. 45–51. doi: https://doi.org/10.15407/pge2021.01.045.

[37] Ramsden, Todd, Darlene Steward and Jarett Zuboy. "Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using the H2A Production Model, Version 2." Technical Report NREL/TP-560-46267. September 2009.

[38] Acharya, A.. "A Review of Renewable Electricity Cost and Capacity Factor Impact on Green Hydrogen Levelized Cost in Off-grid Configuration." Journal of Sustainable Development; Vol. 16, No. 3; 2023. pp. 106-118. doi:10.5539/jsd.v16n3p106.

[39] https://www.iea.org/commentaries/why-clearer-terminology-for-hydrogen-could-unlock-investment-and-scale-up-production.

[40] https://lcss.gov.ly/articles/blog/post-133/?fbclid= IwAR2UC1HXKUIEJzljX7s9XdIJKspEj FsILkiR0c YbXAHXxzZMmFVJGzzIzA0.

[41] https://www.bing.com/images/ etailV2&ccid=jTdfeTQa&id= BE28DF61EF47D726966F4C 5DE1B3DB91498280A2&thid=OIP.