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Public Domain

Green hydrogen economy: Prospects and policies in Vietnam

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- Green hydrogen (H₂) is known as efficient energy carrier for net-zero goal.
- Electrolysis from solar and wind should be the main route of producing green H₂.
- Potential of solar and wind for green H₂ production in Vietnam is presented.
- Prospectives and policies for Vietnam are suggested toward green H₂ economy.

A B S T R A C T

Hydrogen (H₂) plays an important role in the energy transition toward a zero-carbon economy, in which green H₂ could replace fossil fuels in the refining, petrochemical, fertilizer, steel, cement, electricity, and transportation sectors. More importantly, the deployment of green H₂ strategies could ensure energy security and create an efficient way of using national resources. Vietnam has been considered as a country with abundant resources to produce green H₂ but several limitations slow down the transition to a green H₂ economy. Therefore, this article reviews the progress and potential of green H₂ production using solar and wind energy in Vietnam. In addition, the article analyzed the roadmaps and policies of various countries worldwide for the green H₂ economy comprehensively aiming to make policy recommendations for Vietnam. Overall, the green H₂ economy could promote Vietnam's stabilized socio-economic development according to

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Sustainable development
 Net-zero goal
 Vietnamese policy

the expected goals of the new era. Moreover, developing a green H₂ economy could contribute to building the image of Vietnam as a green country, attracting foreign investment and sustainable development.

Introduction

In 2021, the world's energy-associated CO₂ emission reached 37.9 billion tons, as shown in Fig. 1a, which increases the temperature of the Earth resulting in unforeseeable effects for the human future [1]. The difficulties in lowering emissions in sectors related to energy are primarily due to the world's reliance on fossil fuels, which contributed to the vast quantity of CO₂ emissions, particularly in electricity, transportation, buildings, heating, and industry domains [2]. Therefore, decarbonization in the energy system has attracted considerable interest because it could decrease reliance on fossil fuels, reduce negative environmental impacts, and accelerate the search for novel kinds of energy sources in accordance with the Paris Agreement's objective of achieving a society with neutral climate by 2050 [3,4]. Indeed, many governments have promoted the adoption of technologies using renewable energy, which led to great efficiency in decarbonization aiming at a net-zero future [5,6]. Nonetheless, without a bridge, renewable energy can hardly reach a number of regions worldwide. Hydrogen (H₂) could fulfill gaps in the efforts of decarbonization because of its intrinsic versatility as a chemical and non-emissive energy transport, which resulted in the proposal of a novel "green H₂ economy in a society of renewable energy," where H₂ was considered as an important factor with a high market value in a 100% renewable future [2,7]. However, to achieve this ambitiousness, ten times the existing H₂ generation capacity, or about 600 million tons each year, would be required to fulfill the carbon-neutral aims for 2050, as illustrated in Fig. 1b [8].

The term "H₂ economy" refers to a vision where H₂ was produced by water electrolysis and piped to filling stations,

plants, and households, where it was transformed back to electricity utilized in on-site fuel cells (FCs) [9,10]. The H₂ economy is not a far-off concept; instead, the existing H₂ economy would expand to meet the demand in the future. Moreover, the H₂ economy could contribute to the world's energy combination, alleviate the effects of global warming, and bring a hopeful future for decarbonization in multiple sectors [11,12]. Based on previous reports, H₂ was mostly utilized to create value-added products, including methanol, gas-to-liquid fuels, and ammonia, as well as applied in refining and producing steel. However, considering its potential for decarbonization, green H₂ was regarded as a game changer, and it received widespread recognition as a promising clean energy carrier [13].

In the literature, several articles discussed the significance of the H₂ economy, particularly for the green H₂ economy. The capability of the green H₂ economy to generate a virtuous cycle in the production of renewable electricity by using surpluses for green H₂ generation was stressed by Capurso et al. [14], showing positive effects on the capacity parameter of the plant as well as electrical grid flexibility and stability. Thus, the green H₂ economy made an important contribution to the long-term viability of renewable energy. In addition, the adaptability of H₂ applications and uses was considered as a distinguishing feature of the green H₂ economy, playing a role as an infrastructure for the utilization and provision of sustainable and clean energy, which positively influenced any purpose of intervention and field [15]. Therefore, Trattner et al. [16] indicated that the approach to tackle climate change and environmental concerns was to perform two key paradigms, including primary renewable sources of energy and a green H₂ society, leveraging synergy and complementarity of

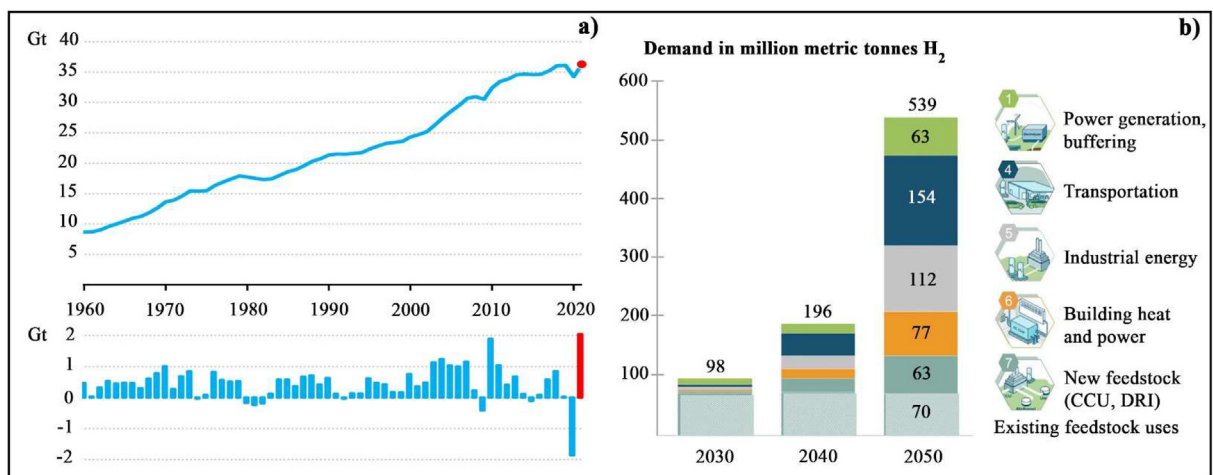


Fig. 1 – (a) Total CO₂ emission from energy sectors and industry [1]; (b) - Global hydrogen demand for 2023–2050 [8].

the abovementioned energy vectors. However, green H₂ has to be adopted in domains, such as the chemical synthesis industry with a substantial need for H₂ worldwide, to increase the penetration rate of hydrogen to energy sectors [12]. In addition, green H₂ can assist decarbonize transportation with FC vehicles that are heavy duty and long range, along with buildings and heating by mixing with natural gas pipelines to heat. In the long run, green H₂ could be applied more in the transportation field in case it was utilized for producing e-fuels for aviation applications and generating high-grade heat for industrial processes [17]. Moreover, green H₂ would take part in the electricity sector, serving as a technique of seasonal energy storage and lowering renewable energy curtailment, enabling near-total decarbonization in the field of energy [2].

Given its industrial portfolio and accessibility to resources, Vietnam is strongly dedicated to decarbonizing its energy and industrial domains to reduce greenhouse gas emissions and enhance air quality. In addition, as part of the national development schemes, Vietnam not only invests in renewable markets but also aims to expand its renewable energy portion of the energy mix. Vietnam is also regarded as a region with high potential for renewable energy sources, including wind, solar, and biomass, which were considered as a potential renewable source of energy source to produce green H₂. Under the impact of the global energy transition trend, the Government of Vietnam took initial steps toward a sustainable economy with commitments to reduce carbon emissions as the goal of developing renewable energy and reducing emissions in the energy sector [18]. Accordingly, H₂ was considered as a solution to develop clean energy and was included in the draft National Energy Development Plan of Vietnam. Thus, opening up a potential market for H₂ development in Vietnam would be promising [19]. However, a roadmap and target for H₂ development must be developed in Vietnam, particularly for potential fields, such as the refining and petrochemical industry, nitrogen, steel, electricity, cement, and transportation.

Despite its numerous benefits, the green economy based on H₂ coped with a number of hurdles, which included commercialization adoption in the Vietnam market, H₂ storage, regulatory legislation, standards, cost, and safety. Thus, this review paper examined Vietnam's existing renewable resources and H₂ energy strategies, as well as suggestions for formulating and developing policy frames, schemes, and action plans at the national and regional scales related to green H₂. The importance of this current work was to provide a policy and technology review and analysis of the green H₂ economy from foregone countries aiming to offer proposals to Vietnam about formulating policies on energy conversion for developing a green H₂ economy at the national level.

Potential for hydrogen production in vietnam

Current demand for hydrogen in vietnam

At present, in Vietnam, grey hydrogen and brown hydrogen were produced and utilized primarily in oil refineries and fertilizer plants. A small amount of hydrogen was also used in

steel, float glass, electronics, and food factories, accounting for about 0.5% of Vietnam's current total H₂ demand [19]. For fertilizer plants, H₂ was considered as the basic raw material for the synthesis of ammonia, which was then further converted to produce urea [20]. The amount of H₂ generated from reforming was closely related to CO₂ content in natural gas. Therefore, an additional source of H₂ must be ensured to simultaneously process hydrocarbon and CO₂ components in the gas for fertilizer production. Thus, the cost-effective production of additional H₂ was a key requirement to utilize CO₂-rich natural gas sources as raw materials for fertilizer plants. The current H₂ demand for fertilizer and oil refineries in Vietnam is shown in Fig. 2 [21].

Regarding the power generation industry, electricity produced from H₂ was considered clean electricity to replace coal power sources or used in areas that were not favorable for the development of renewable energy [22]. In particular, H₂ could be considered as a useful energy carrier that could be produced by converting excess renewable electricity. Although electricity produced from H₂ in Vietnam to date had a small output, the demand for H₂ for electricity generation in Vietnam would reach 2200 kta by 2050 [19]. In the steel industry, coal was used as a reducing agent to convert iron ore raw materials, which was considered as the main cause of carbon emissions in steelmaking with an emission level of about 122.5 million tons of CO₂ by 2025 and around 132.9 million tons of CO₂ by 2030, which comprised 17% of the total national emissions [23]. Therefore, H₂ could be seen as a great option to lower CO₂ emissions for this industry. In Vietnam, the demand for H₂ in producing steel could reach 1000 kta by 2050. Similar to the steel industry, cement production was an area that had high energy consumption, which emitted a large amount of CO₂. Almost half of the CO₂ emitted from cement generation was due to the burning of raw materials, primarily limestone. The burning of fuel for furnace combustion was composed of approximately 40% of the total CO₂ emission [24]. Therefore, H₂ was regarded as a lever that significantly decreased CO₂ emissions from cement industry. In the case of Vietnam, the demand for H₂ for the generation of cement could reach 2800 kta by 2050 [19].

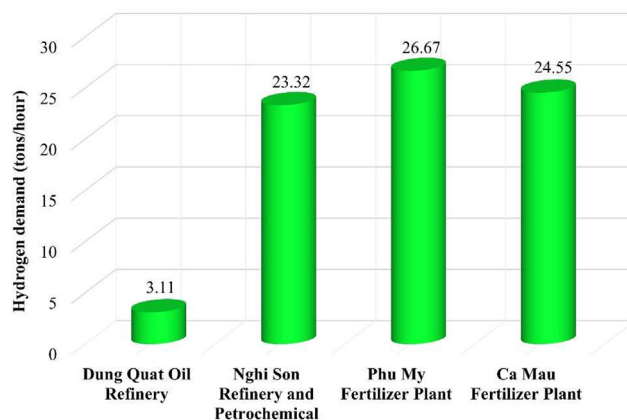


Fig. 2 – Hydrogen demand for some industry domains in Vietnam [21].

H₂ was known as a non-poisonous, eco-friendly energy carrier with a high specific energy per mass, which indicated that 9.5 kg of H₂ had the same energy concentration as 25 kg of gasoline [25]. Moreover, Balat et al. [26] pointed out that the physical and chemical characteristics of H₂ demonstrated a wide spectrum of flammability when compared with methane and gasoline. Consequently, H₂ engine could work more efficiently on lean blends in comparison with gasoline engines. During utilization, H₂-fueled vehicles showed no emissions, thereby improving the air quality [25]. Furthermore, FCs using hydrogen could mitigate or remove CO₂ and greenhouse gas emissions from road transport vehicles [27,28]. Thus, H₂ fuel-cell technology has received great attention in recent years because of its high efficiency and low emissions. In 2020, more than 25,000 H₂ fuel-cell electric vehicles and 540 H₂ fueling stations were distributed worldwide. Electric vehicles powered by H₂FCs would constitute 25% of the global market share by 2040 and reach approximately 400 million vehicles by 2050 [29]. Nevertheless, the amount of H₂ held on the working board was limited because of the low density of H₂ gas, which inhibited the wide application of FCs, although H₂ storage was known as the fundamental technique toward the utilization of hydrogen FCs [30]. In the case of Vietnam, H₂FC vehicles were more expensive compared with the average income of the people. Moreover, charging stations were not distributed properly and widely to meet the needs of users. Therefore, consumers were not really attracted by vehicles running on H₂ FCs.

Considering that H₂ would begin to be piloted for potential fields from 2025, the rate of H₂ consumption would reach 20%–30% by 2050, and the green H₂ market in Vietnam could reach around 22 million tons per year by 2050, which was equivalent to 2.8% of the world's H₂ demand [19]. The development of H₂ in Vietnam's key sectors, such as transportation, cement, electricity, steel, refining, petrochemicals, and fertilizer production, could decrease the total national CO₂ emission by 5.4% by 2030. In addition, H₂ development in Vietnam could facilitate the development of economic and social factors as well as related industries.

Potential for green hydrogen in vietnam

Hydrogen (H₂) is divided into several color shades depending on its H₂ generation approach, sources of energy source, and environmental effects [31,32]. In particular, brown H₂ is created through gasification from hydrocarbon-rich feedstock, and each ton of brown H₂ is observed to discharge 10–12 tons of CO₂ into the atmosphere. Meanwhile, blue H₂ is created by steam-reforming natural gas, in which the captured CO₂ is approximately 85%–95%; however, the long-term effects of storage were unknown, and they might have a harmful effect on the ecology and climate [33,34]. Moreover, coal gasification produces black H₂, and the rest of the gases could be discharged into the air [35,36]. Grey H₂ is generated from non-renewable fossil fuels, and the created CO₂ is not collected; instead, it is discharged directly into the atmosphere [37]. Furthermore, green H₂ is widely regarded as a potential fuel for sustainable development in the future and energy conversion because it could be created from water and renewable sources of energy via electrolysis, which generates no greenhouse gas emissions [38]. At present, various projects

are conducted worldwide to manufacture green H₂ by utilizing renewable energy sources such as solar and wind [39]. In 2020, the majority of H₂ (95%) was generated from non-renewable fossil fuels, particularly through steam reforming of natural gas, which released 830 million tons of CO₂ per year, with the remainder generated from renewable resources such as water electrolysis [38,40]. The main H₂ generation technologies and their applications are shown in Fig. 3.

Vietnam has a diverse range of renewable energy resources, including biomass, solar, wind, hydroelectricity, and geothermal [41], all of which could be used to produce green H₂ [42]. Based on the current and expected dissemination in Vietnam, as well as the tendency of green H₂ generation methods via water electrolysis with the use of solar and wind in recent years [43], wind and solar energy resources are regarded as potential options for producing green H₂ in Vietnam. In addition, Vietnam could benefit from being among the countries in the distribution of the most sunlight per year on the radiation map provided by the world. Therefore, it is considered as a country with great potential for solar energy. Based on the radiation map developed by the World Bank, the potential of solar energy in Vietnam is theoretically remarkable [44]. On average, the total solar radiation in Vietnam is approximately 5 kW/h/m² per day in the central and southern provinces and approximately 4 kW/h/m² per day in the northern provinces/cities. From below the 17th latitude, solar radiation is not only abundant but also stable throughout the year, although it reduces by about 20% from the dry season to the rainy season. In addition, the number of sunshine hours each year in the North is in the range of about 1500–1700 h, whereas in Central and Southern Vietnam, it ranges from around 2000 to 2600 h per year [45]. Thus, the exploitable potential for electricity production from solar energy in Vietnam was approximately 13,000 MW [46]. For wind energy, Vietnam has the largest wind potential in Southeast Asia as its total wind power potential is approximately 513,360 MW (with more than 8% of Vietnam's area ranked as having a very promising potential for wind power [47]), which is 200 times the capacity of Son La hydropower plant and more than 10 times the total predicted capacity of Vietnam's electricity industry by 2020 [48]. Furthermore, Vietnam has an average annual wind speed greater than 6 m/s at an altitude of 65 m, whereas the potential for wind energy at an altitude of 80 m above sea level with a speed of 8 m/s is 1300 GW. In particular, the wind potential is observed to reach a high level in the coastal area from Ninh Thuan to Ba Ria-Vung Tau with an annual average wind speed of 8–10 m/s and an average annual energy density of 600 W/m² to over 700 W/m² [48]. Besides, Vietnam could develop approximately 27 GW of wind power on land, corresponding to an average wind speed of 5.5–7.3 m/s [47]. Given the potential of solar and wind in Vietnam, green H₂ production using solar and wind energy is very promising. In a recent study by Vu et al. [49], they reported that the hybrid power system installed in industrial zones in Can Tho, Quang Nam, and Binh Thuan provinces could produce approximately 17 tons of green H₂ per year to supply the FC operation depending on the potential of solar energy in each province. In general, solar and wind potential along with map of solar and wind energy projects in Vietnam are depicted in Fig. 4.

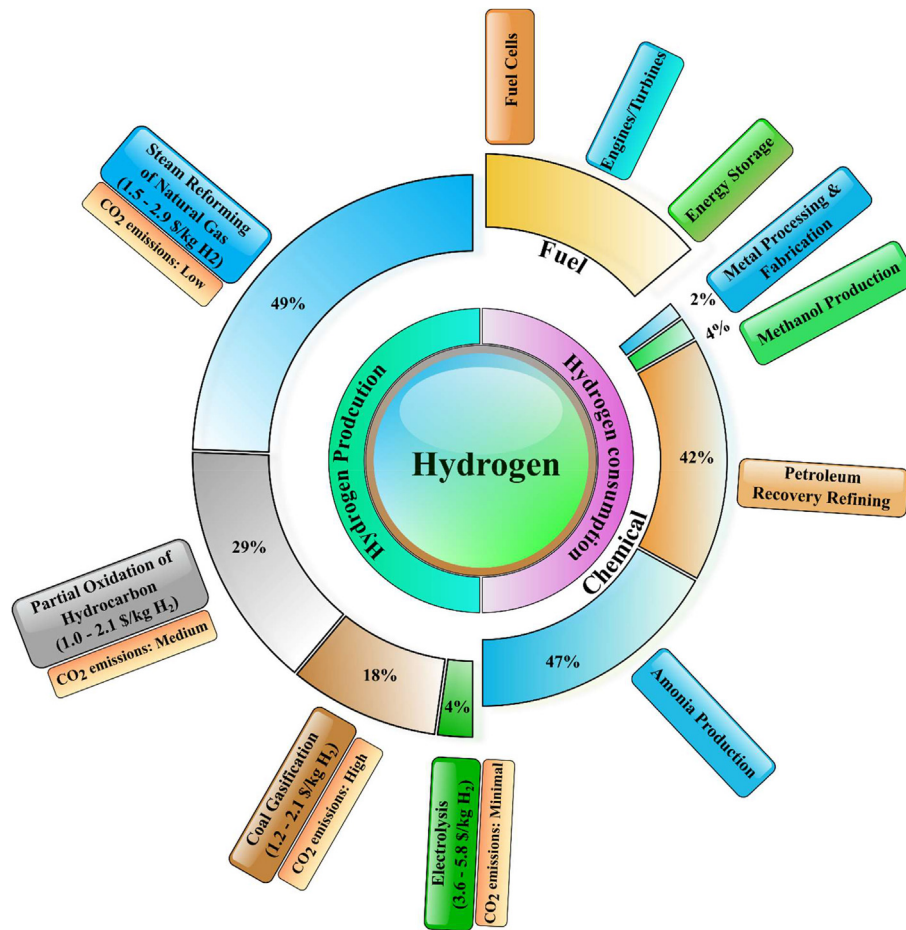


Fig. 3 – Hydrogen color shades along with their production pathway and applications [38]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The aforementioned data indicate the huge potential for solar and wind energy in Vietnam, emphasizing that utilizing these kinds of energy for green H₂ production to meet the increasing demand for hydrogen in Vietnam is considered an effective solution.

Cost of green hydrogen

Green H₂ would also play an important role in the integration of renewables and transportation. When electrifying the transportation field, FC electric vehicles running on green H₂ brought many significant benefits over electric vehicles using batteries. Furthermore, hydrogen has been widely utilized in a variety of industries, including fertilizers, refineries, metals, and chemicals [52]. Notably, the replacement of traditional fossil fuel sources with green H₂ with a low-carbon footprint showed a huge emission reduction opportunity. Moreover, the combination of the current market for industrial H₂ and the possibility of exporting H₂ to pioneer markets such as China, the European Union, South Korea, and Japan, in which H₂ is increasingly used as energy, was observed to bring novel industrial opportunities for Vietnam while lowering the risk associated with setting up H₂ supply chains and investing in relevant infrastructure [53]. Nonetheless, green H₂ techniques

are uneconomically practical because the existing technological equipment expenses to produce, store, and distribute green hydrogen are not yet in mass production. Hence, such techniques remain expensive, which results in large capital costs for green hydrogen-based systems, leading to high prices for produced green hydrogen. Accordingly, the economic competitiveness of hydrogen is diminished compared with other fuels, particularly natural gas, and the widespread adoption of green H₂ technologies is limited. Furthermore, other essential aspects differ by country, including the conditions of the energy market, labor and financial expenses, and policy and institutional frameworks (particularly environmental criteria, taxes, renewable energy incentives, and subsidies) [54]. The expenses of energy projects often increase within a particular spectrum, necessitating a dedicated assessment of the expenses for green H₂ energy. Thus, the first and most crucial obstacle remained the economics of green H₂ [55].

At present, on-site steam-methane reforming was considered as the widely utilized H₂-generating technology in the EU industry because of the developed technology and low-cost natural gas, that is, the price varied from €2 to €3/kg [54]. Steam-methane reforming emitted CO₂, so the generated H₂ was not environmentally friendly [56]. As mentioned previously, green H₂ produced by the electrolysis of H₂O molecules

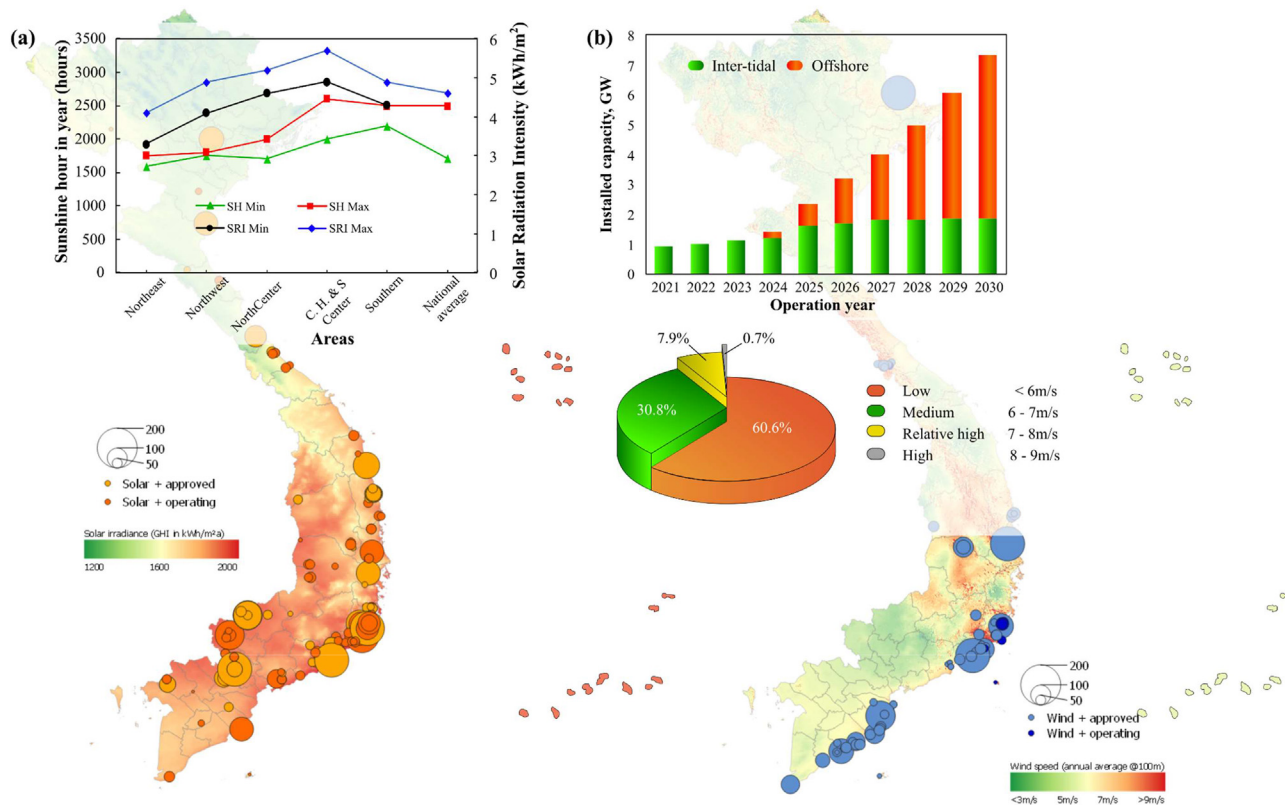


Fig. 4 – (a) - Solar potential along with map of solar energy projects in Vietnam [45,50], and (b) - Wind potential in Vietnam along with map of wind energy projects in Vietnam [47,50,51].

has emerged as the preferred approach for future H₂ synthesis. However, the cost of green H₂ is higher than that of other H₂ types. Pastore et al. [57] pointed out that green H₂ production at a competitive price required a levelized cost of electricity less than €30/MWh, but it was around 2.3 times the current EU natural gas price. Based on certain projections, the levelized cost of brown, blue, and grey H₂ would be approximately €1.7–2.4/kg, whereas green H₂ that was generated using water electrolysis driven by wind and solar techniques would cost €2.3 to €4.3/kg [57,58]. Therefore, a large number of essential research and development have been conducted to minimize current expenses by promoting technologies. The majority of electrolytic green H₂ costs result from capital investment in equipment and the cost of electricity [59,60].

Power costs had greater impacts on a large-scale system compared with capital expenses. In an experiment, Rahil et al. [61] studied green H₂ synthesis utilizing off-peak electricity generated by a wind power production plant. They demonstrated that off-peak electrolysis might result in the lowest cost of green H₂ generation at \$3.83/kg, whereas off-peak wind could cost \$0.07/kWh. When grid electricity was used at an expense of \$0.16/kWh, the cost of green H₂ reached \$9.10/kg [53]. Along with the development of technologies, the cost is projected to be at least \$2/kg green H₂ by 2030 under the assumption of better and less expensive electrolyzers with a levelized cost of electricity of \$20/MWh [62], showing that the electricity costs were a significant cost component in the electrolysis of green H₂. The efficiency and capital expenses of electrolyzers, in conjunction with capacity use, were

considered as other defining expenditure factors. In addition, other expenses, such as water, labor, and land, played a minimal role in hydrogen generation costs [36]. In addition, capital expenses were reduced by using an electrolyzer, which ranged from \$500–1400/kW (2019) to \$400–850/kW (in 2030) for alkaline electrolyzers, whereas the prices for polymer electrolyte membrane electrolyzers ranged from \$1100–1800/kW (2019) to \$650–1500/kW (in 2030) [36], showing lower capital costs. Moreover, in the future, the ever-increasing demand for electrolyzers and the advancement in technologies could lead to the substantial decrease in green H₂ production prices [63]. Notably, electrolyzer capital expenses for a major utility-scale system were predicted to decrease by 40%–60% by 2030 [64,65]; nonetheless, the major problem was market conditions, which required operators to use plants for over 2000 h per year to achieve a revenue greater than the entire cost [66,67]. The sources of energy determined the capacity employment parameters for electrolyzers. An electrolyzer powered by stand-alone renewable sources of energy supplemented by deep storage or utilizing the grid as a backup would be capable of operating at high rates of capacity, potentially surpassing 90% [63]. For example, an electrolyzer powered by a wind farm showed a capacity factor of nearly 45%, whereas a solo solar farm could have a capacity factor of approximately 30% [68].

In the case of green H₂-powered vehicles, the manufacturing and distributing cost could directly affect the green H₂ price. Given the low sale volume and high expenses of manufacturing and distribution, the green H₂ price at

gasoline stations was likely to be high in the first several years of introduction; for example, fuel stations in Germany were currently charging approximately 10€/kg [54]. Based on projections, in the field of mobility, the consumption of green H₂ in the EU market might reach approximately 750 ktons per year by 2030 [56]. Based on the HyWays project [69], it could be between 9% and 13% of the EU's total fleet by 2030, or 12–25 million vehicles would be vehicles running on an H₂FC. Therefore, by 2030, H₂ would be the most competitive green option in a variety of applications, and the implementation of a carbon tax would allow green H₂ generation to become more competitive compared with brown or grey and blue H₂ [70]. In addition, the International Energy Agency (IEA) [64] demonstrated that the offshore production of H₂ was a viable alternative to the costly utilization of electricity cables. For example, with price declines for offshore electricity production, the cost of producing H₂ in the North Sea could drop to €2/kg by 2030. However, the use of H₂ was highly tied to investments, which could be driven not only by carbon expenses and demand but also by the prices of electricity as well as electrolyzer capital expenses and efficiency [71,72].

In Vietnam, the advancement of green H₂ and the development of H₂ fuel-cell vehicle supply chains open up new avenues for economic growth and employment creation. Furthermore, green H₂ production via electrolysis almost always takes advantage of the most cost-effective available electricity production options rather than high-expense installations of renewable energy systems in unsuitable regions. As reported, Vietnam has shown great potential for offshore wind power development with a total technical potential estimated at 162.2 GW. The forecast indicated that the price of offshore wind power in Vietnam could drop to 1174–1644 VND/kWh by 2030 and even below 470–740 VND/kWh by 2050.¹ These values were equivalent to the price of green hydrogen produced from offshore wind power, which could be decreased to \$8–12/kg in 2030 and \$3–6/kg in 2050 [73]. Consequently, future prices are significantly lower than that of the current range. Accordingly, Vietnam is recommended to outline a strategy and appropriate policies for green H₂ development in the future.

Vietnamese policy and strategy toward a green hydrogen economy

Policy and roadmap of countries in the world

On December 8, 2020, the Green Hydrogen Catapult Initiative was launched by seven leading green H₂ developers aiming to expand the scale of green H₂ production up to 50 times before 2026 [74]. With regard to absolute numbers, the increase in output indicated the implementation of 25 GWs of green H₂ and a drop in green H₂ generation costs less than the \$2/kg per kilogram threshold [75]. Based on IEA forecasts, the worldwide green H₂ market would develop at an exponential rate in the next years, reaching a value of \$10 billion in 2028, and green H₂

could meet 24% of the world's demand for energy by 2050 [76,77].

China was considered a prominent participant in Asia's renewable H₂ economy and an active player in the International Partnership with regard to Hydrogen Economy. China announced a practical and low-cost technology that reformed methanol into H₂ [78]. Several National Basic Research Program projects involved the use of FCs and the lab-scale synthesis of H₂ from water using solar energy. Another strategy was related to fossil fuel H₂ along with the FC technique, as well as enhanced production of H₂ for motor applications [79]. As estimated, the strategies of China in a long term focusing on the H₂ economy would be implemented after 2050, in which H₂ energy was found to be a part of the national energy system [80]. In its energy development policies, China drew up a plan for the widespread utilization of hydrogen and made significant investments in research on H₂ and FCs [81]. In March 2022, China officially published the plan for a modern energy system aiming to advance decarbonization efforts by 2025 with a focus on H₂ energy [82]. In addition, China set up a plan of constructing more H₂ refueling stations to attain the goal of putting 50,000H₂ fuel-cell vehicles by 2025 [83].

Moreover, a European Green Deal Package with trillion dollars adopted in 2019 sparked a surge in investor interest in green H₂ [77]. In addition, the European Commission issued a strategic road plan for hydrogen in July 2020, which was predicted to increase from below 2% to 13%–14% by 2050 [84]. EU hydrogen policy was considered the most ambitious green H₂ plan in the world, aiming for 40 GW of green hydrogen by 2030 [77]. Fig. 5 shows the European roadmap for fuel cells and hydrogen, which divided the milestones into two sections, including “Development and deployment of fuel cell and hydrogen system” and “generation and distribution of hydrogen.” Moreover, the road map predicted that directly producing hydrogen from renewables would begin by 2050 [85].

As shown in Fig. 5, the EU goal was to decarbonize current H₂ generation by 2024 and to incorporate H₂ into other industrial processes along with heavy-duty transportation. In 5 years from 2025, H₂ would become an essential component of the novel renewable energy system, with novel applications in the fields of transportation and steel. In achieving the above-mentioned objectives, the plan was primarily dependent on green H₂, which was generated through electrolysis using renewable energy. The EU set a target of 40 GW of electrolyzers producing green H₂ in Europe, and water electrolysis was the only method among green generation ones ready for being applied on a commercial scale, despite several challenges in promoting the manufacturing and operating efficiency [86]. The net-zero of the EU could enable H₂ to enter the energy economy and lower expense barriers, promoting the production of green hydrogen [87,88]. Moreover, although a 70% decrease in the expenditure of renewable energy generation was predicted because of advances in materials and other technical problems [89], blue hydrogen would almost certainly make room for green hydrogen to meet the decarbonization targets by 2030 [67].

In the United States, the H₂ energy produced and consumed was approximately 10 million tons in 2020, making up slightly over 1% of the whole energy consumption [90].

¹ Exchange rate from USD to VND at the time of writing this paper.

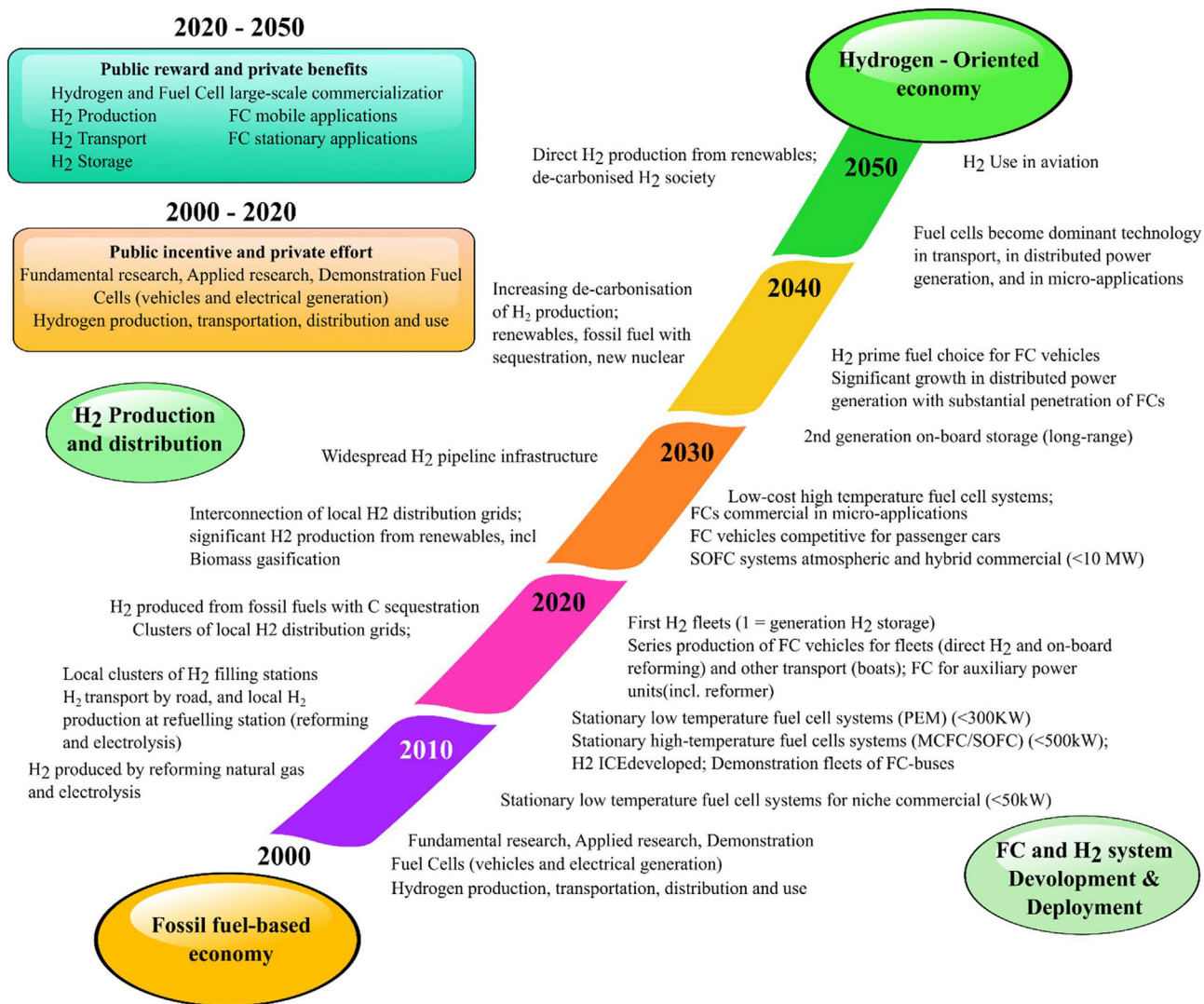


Fig. 5 – Roadmap of hydrogen energy in EU [85].

Given the considerable use of additional natural gas preserves and shale gas [91], plants using natural gas infrastructure could produce around 95% of hydrogen, whereas only 5% was generated through the chlor-alkali industry, water electrolysis, and by-products from chemical processing units. Moreover, in 2020, over \$150 million was spent to support R&D for several critical techniques for the hydrogen economy [90,92]. Furthermore, the Department of Transportation of the United States set up a competitive grant program to strategically implement publicly accessible vehicles using electric charging and H₂ fueling infrastructure along the assigned Federal Highway Administration Alternative Fuel Corridor. A tax credit was also considered available for alternative fuel sold for utilization or employed as fuel to run a motor vehicle until December 31, 2024. For example, alternative fuel-liquefied H₂ was eligible for a \$0.5 per gallon tax credit. Moreover, the Hydrogen Shot was founded as part of the United States Department of Energy's Energy Earthshots Initiative, aiming at mitigating green H₂ costs by 80% to \$1 per kilogram during 10 years. Hydrogen Shot also concentrated on a variety of projects that addressed technical gaps in the generation,

distribution, storage, and technologies of H₂. In addition, the Department of Transportation of the United State set up a pilot grant program to purchase electric or low-emission ferries, as well as the electrification or other emission reductions of current ferries. Ferries with low emissions must use alternative fuel-like H₂. In addition, the program Regional Clean Hydrogen Hubs, also known as H₂Hubs, contained up to \$7 billion in funding to create six to ten green H₂ centers around the United States. Thus, H₂Hubs could be a key driver in supporting communities across the nation to take advantage of clean energy investments, well-paid jobs, and enhanced energy security as part of a larger H₂ hub program with \$8 billion funded by the Bipartisan Infrastructure Law [93].

The Australian Government's concern about H₂ initially emerged in 2003, when the Department of Tourism, Industry, and Resources commissioned a National Hydrogen Investigation [94]. In November 2019, Australia introduced a national H₂ scheme that was agreed upon by state, territory, and federal governments, suggesting a vision for a safe, clean, competitive, and innovative H₂ economy that could assist

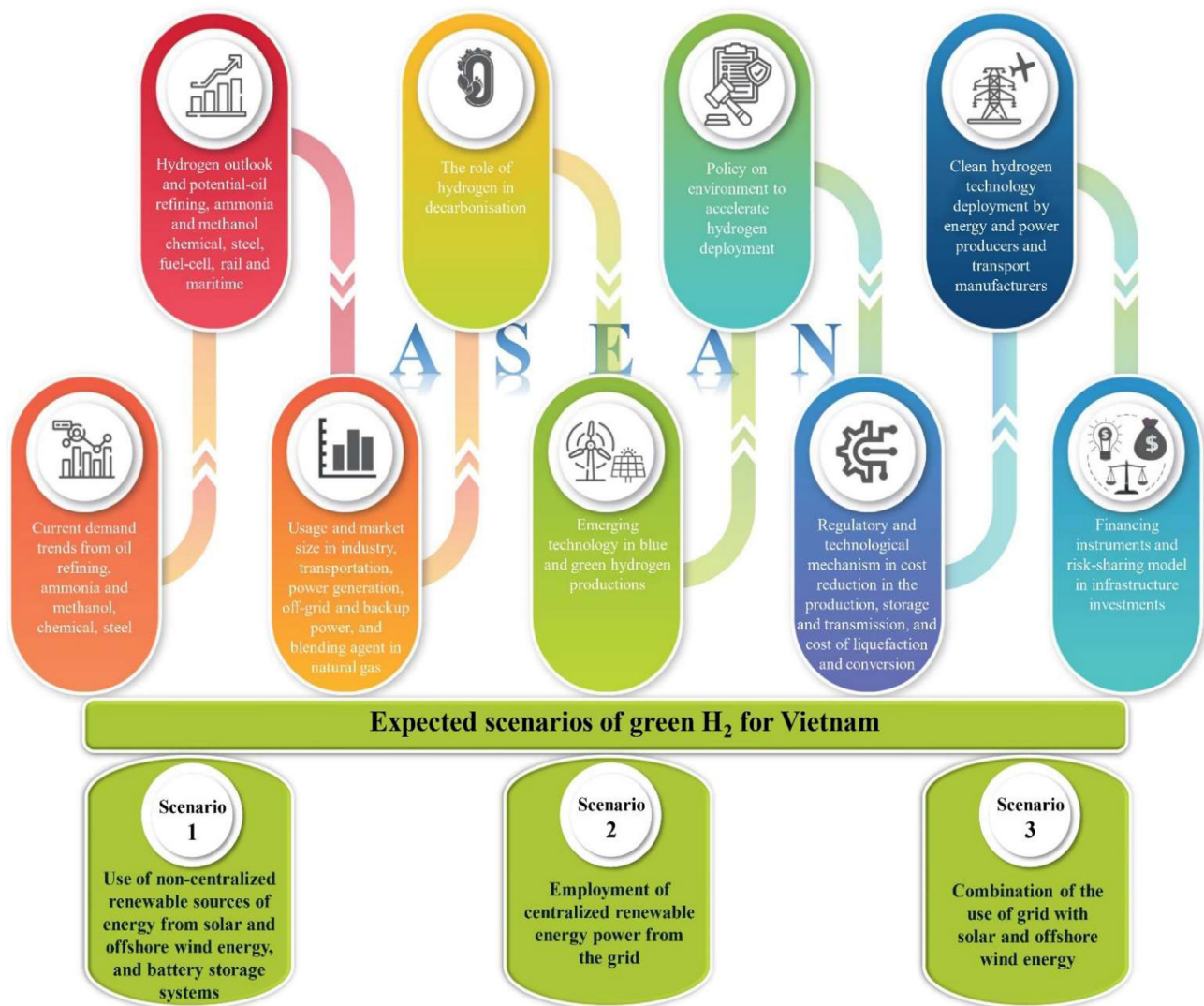


Fig. 6 – Expected scenarios of developing green H₂ economy for Vietnam based on ASEAN orientation [99,102]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Australia in transitioning to a low-emission, affordable, and sustainable future [95]. The strategy emphasized the importance of collaboration among the fields of government, industry, and education to develop an H₂-ready workforce for Australia. Furthermore, preliminary data obtained from the net-zero Australia project showed that an increase in high-skilled employment was necessary in the next decades to support the renewable energy and H₂ domain [96,97].

Vietnamese policy implication and suggested roadmap

Vietnam was taking the initial steps to transit energy, from traditional to renewable, or green energy, in which the development of a green H₂ economy was regarded as a key goal of Vietnam in the near future. As forecasted, the final energy demand in Vietnam by 2050 would be equivalent to around 144–170 million tons of oil, in which H₂ energy comprises about 5.6%–6.2% [98]. Therefore, the application of green H₂ to transportation and industry could help Vietnam reduce about 324.4 million tons of CO₂ by 2050, thereby

contributing to the net-zero goal in the entire energy sector [99]. Given the abundant renewable sources in Vietnam, the development of green H₂ could start with developing offshore wind power and solar.

In achieving the goal of developing green H₂ energy, the Vietnamese government issued Resolution No. 55-NQ/TW dated 2020 on the orientation of the National Energy Development Strategy to the end of 2030, with a vision to 2045. Vietnam also published a list of high-priority technologies for development, including hydrogen energy sources by 2050 [100]. According to the National Energy Development Strategy for 2030, with a vision for 2050, the development of H₂ energy was clearly directed. In addition, the National Energy Plan set a target that by 2050, H₂ production could reach about 25 million tons, and synthetic fuels originating from H₂ would reach approximately 2.5–2.9 million tons. Accordingly, H₂ fuel and H₂-derived synthetic fuels were used in electricity generation, transportation, industry, and residential and commercial buildings to accelerate the energy transition and to step-by-step decarbonize the economy [98]. Moreover, the

Table 1 – Suggestions of policy and roadmap to develop green H₂ economy in Vietnam.

Order step	Suggested policy and roadmap	Time frame
Step 1 – “Walking”	<ul style="list-style-type: none"> ➤ Including green H₂ in the national energy plan to formulate a legal framework; ➤ Promulgating legal regulations on the management of green H₂ development activities according to the scope and subjects in the energy area; ➤ Evaluating the reality of demand for green H₂ in the national economy; ➤ Raising social awareness of green hydrogen, training and developing human resources in the green H₂ economy; 	Now - 2030
Step 1 – “Running”	<ul style="list-style-type: none"> ➤ Setting specific plans for storage technologies and transportation infrastructure, taking into account the needs and common use mechanism for green H₂ development; ➤ Introducing a priority list for green H₂ development projects and related fields; ➤ Implement preferential tax policies for enterprises producing green H₂; ➤ Developing standards, technical regulations, and safety regulations aiming to ensure synchronous development of the green H₂ value chain; 	2031–2040
Step 1 – “Speeding up”	<ul style="list-style-type: none"> ➤ Developing the financial support projects serving the development of the green H₂ value chain and infrastructure; ➤ Implementing tax incentives and financial support for H₂ fuel-cell vehicles manufacturers and buyers; ➤ Imposing the CO₂ tax on fossil fuels to ensure that green H₂ could compete with traditional fossil fuels; 	2041–2050

increase in carbon tax should be an efficient solution to achieve a clean, green, and healthy business environment. Based on previous reports, the carbon tax should be increased to 1275–2,55 million VND/t CO₂ to achieve a green H₂ price of 17,830–25,500 VND/kg [101].² Furthermore, the H₂ energy development roadmap was divided into two phases: Phase 1 from 2020 to 2030, small-scale H₂ projects would be developed with approximately 20,000–25,000 tons; and Phase 2 from 2031 to 2050, H₂ production would be promoted by using renewable electricity technology and coal gasification [98]. Based on the general strategy of ASEAN, UNDP and the Vietnam Energy Institute also pointed out three scenarios for green H₂ development in Vietnam based on renewable energy supply for electrolysis, as depicted in Fig. 6.

In all three aforementioned scenarios, in case the electrolyzers operated at 90% capacity continuously, at least 18.78 million tons of green H₂ could be produced by 2050. However, given the production capacity limitations, if the employment of only green H₂ is not enough for the H₂ demand in Vietnam; therefore, many other approaches in the energy sectors should be combined [99]. In achieving the net-zero strategy shortly, the Vietnam government should issue suitable policies, a roadmap, and solutions relating to the goal of green H₂ development. In general, in the context of Vietnam moving toward net-zero emissions by 2050, green H₂ industrial development would not only reduce greenhouse gas emissions but also allow Vietnam to reach a low-carbon economy as expected [103]. The order steps for the green H₂ economy are presented in Table 1.

Conclusions and recommendations

Green H₂ is utilized as a feedstock in a number of major industries, and it could be the “missing link” in supplying large

amounts of renewable energy to many sectors that would struggle to decarbonize. The green H₂ economy has progressed swiftly through incremental advancements, and it greatly enhances the security and supply of energy in accordance with zero-emission terms. Furthermore, green H₂, produced from renewable resources, effectively substitutes fossil fuels and provides the potential for sustainable development of energy in the future. Besides, as a clean energy carrier, green H₂ could alleviate all difficulties associated with conventional fuels, including environmental changes, energy security, and pollution, and it can mitigate climate change.

This study aims to present Vietnam’s potential and policy in shifting to a green H₂ economy. In addressing not only the energy issue, but also existing economic sustainability, Vietnam should explore and develop all energy sources available. In addition, the generation of green H₂ in Vietnam is viable because of the country’s abundant renewable sources of energy, especially offshore renewable energy. Therefore, generating electricity through offshore renewable energy and then using electricity for electrolyzing water into green H₂ could be a much more profitable solution than the case of transporting electricity offshore to the inland. However, it should take account into technology and engineering factors, and investment terms aiming to limit the unexpected negative impacts. Moreover, more breakthroughs in the H₂ production, storage, transportation, or distribution section are necessary to build up a green H₂ economy. In this aspect, the government also plays an important role in expanding the scale and deploying reasonable policies for the green H₂ economy. On the way toward the green H₂ economy, it should be noted that the adoption of novel technology would necessitate incentives and subsidies for not only technology providers but also customers. Alternatively, the rate of transition to H₂ could be determined by the magnitude and consistency of development toward the green H₂ economy. Furthermore, low levels of public acceptance problems about safety and financial stability must be addressed before implementing green H₂ energy. Due to these reasons, Vietnam should look for a

² Exchange rate from Euro to VND at the time of writing this paper.

harmony and balance point between the existing economy and the green H₂ economy to have a “spectacular breakout” in shifting energy progress. In general, the creation of a green H₂ economy would address numerous hurdles while opening up new opportunities for a low-carbon economy in Vietnam. Nonetheless, future research could look at the establishment of multi-field symbiosis in the world and ASEAN region for the green H₂ economy in Vietnam.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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