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Research article

Assessing factors influencing green hydrogen conversion at Vietnam's gas turbine power plants using combined SWOT-AHP analysis method

Duong Doan Ngoc[1,2], Kien Duong Trung[2,*], Phap Vu Minh[2,3] and Thao Nguyen Van[4]

[1] Electricity and Renewable Energy Authority, Ministry of Industry and Trade, Hanoi, Vietnam
[2] Electric Power University, Ministry of Industry and Trade, Hanoi, Vietnam
[3] Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Hanoi, Vietnam
[4] Institute of Energy, Ministry of Industry and Trade, Hanoi, Vietnam

* **Correspondence:** Email: kiendt@epu.edu.vn; Tel: +84912661982.

Abstract: At COP26, Vietnam committed to achieve net zero emissions by 2050. Up to now, several strategic policies and master plans concerning energy and power development along with emission reduction have been introduced. The national power development plan for the 2021–2030 vision to 2050 (PDP8) has directed for gas-to-hydrogen fuel conversion at gas turbine power sources in the national power system when the technology is commercialized and the cost is appropriate. Therefore, gas turbine power plants (GTPPs) with a total capacity of approximately 32.4 GW by 2050, using domestic natural gas and imported liquefied natural gas (LNG), will be expected to switch to using green hydrogen (GH2) to cut greenhouse gas (GHGs) emissions. This study uses the SWOT analysis and analytic hierarchy process (AHP) method to quantitatively analyze and examine the factors influencing the perspective of GH2 conversion at CTPPs in Vietnam. Research results show that among the four groups of Strengths, Weaknesses, Opportunities, and Threats being examined, the most influencing one is Weaknesses with the highest weight of 0.381, followed by Threats (0.343), suggesting that the GH2 conversion ambition will be facing significant challenges and difficulties. At the level of element factors in the groups, the lack of infrastructure and insufficient legal framework/specific incentive mechanisms are the biggest weaknesses, with weights of 0.362 and 0.326, respectively, while the consistent policies of the state and abundant potential of renewable energy resources, weighing 0.446 and 0.235, respectively, are Vietnam's prominent strengths. Additionally, remarkable opportunities include the effective exploitation of available renewable energy resources (0.338) and great contribution to reducing emissions (0.288), while the main challenges remain the lack of capital (0.471) and high GH2 cost (0.284). The research results clarify the typical problems of a developing country like Vietnam in the global energy transition trend toward carbon neutrality: high potential of renewable energy sources, great political determination, and ambitious goals for green growth, but significant difficulties and challenges due to the low starting point and limited technological and financial resources while energy demand is constantly increasing. Thus, some strategic solutions are proposed, including taking advantage of internal strengths to avoid/limit external threats, making the most of strengths to exploit opportunities, and minimizing weaknesses to take advantage of opportunities and to limit the threats.

Keywords: net zero; fuel conversion; green hydrogen; gas turbine; SWOT; AHP

1. Introduction

At COP26, Vietnam announced its intention of achieving net zero emissions by 2050. Following the world's trend and in accordance with the conditions to fulfill its commitment, Vietnam introduced several policies to promote energy transition. Accordingly, dozens of solutions have been considered, such as promoting electrification of various energy-using fields, strongly developing renewable energy (RE) and low-emission power sources, and implementing energy efficiency programs. In particular, developing the production and application of GH2 in the energy industry is one of the solutions that contributes to ensuring energy security and achieving national goals on climate change and green growth [1,2].

The PDP8 provides a roadmap for converting fuel at GTPPs from natural gas to hydrogen when the technology is commercialized and cost is appropriate. Accordingly, 7 GW of GTPPs firing domestic gas and approximately 25.4 GW of CTPPs using LNG are expected to switch to using GH2 by 2050 [3]. This objective deals with practical problems facing Vietnam's electricity industry in the medium and long term—meeting the target of reducing emissions of the power system while continuing to maintain the operation of dispatchable power sources to run at base load until 2050. Although Vietnam has a number of basic advantages and favorable conditions for developing hydrogen energy, the process of hydrogen conversion at GTPPs is anticipated to be very complex and challenging, thus requiring comprehensive consideration and in-depth evaluation, as well as strategic assessment. For this purpose, the method of SWOT strategic analysis is usually adopted.

SWOT analysis is commonly used when researching and considering energy policy on a regional/national scale or developing/application of a specific type of energy, including hydrogen energy. Xunpeng Shi assessed the perspectives of energy mix in the ASEAN, highlighting the paradox of its fossil fuel-dominated future when contrasted with its aspirations to move toward a green energy mix, and reviewed green energy strategies using the SWOT analysis method [4]. Other authors explored and assessed strategic considerations for the development of various types of renewable energies in different countries [5–7]. Particularly for hydrogen energy, Khan and Al-Ghamdi used the SWOT method to examine the hydrogen economy perspective in the GCC region, finding that GCC countries have the resources and opportunity to be leaders in hydrogen but will need to take risks when competing globally [8]. In another study, the analytical SWOT method was used to analyze the strengths, weaknesses, opportunities, and threats of the hydrogen economy in China; then, strategies were proposed by exerting strengths, mitigating weaknesses, exploiting opportunities, and avoiding threats [9]. It is noted that the SWOT method does not quantitatively evaluate each of the decision-making factors, making it difficult to assess which factors influence strategic decisions the most. To solve this problem, combining the SWOT method with AHP provides a quantitative measure of the importance of each factor in decision-making, improving the usability of SWOT analysis. The AHP method is a quantitative analysis determining the level of importance of each element/criterion/factor, checking consistency in assessment, and reducing bias when making decisions in complex situations [10–13]. Applications of AHP can be found in a number of decision-making studies relating to the energy sector worldwide [14–18], where authors quantitatively investigate relevant factors and criteria, determining the prioritization of those before suggesting strategic implications. Chang and Huang used the quantified SWOT analytical method to assess the competing strength of studied subjects and then suggested an adoptable competing strategy [19]. Pesonen et al. [20] employed the SWOT-AHP method in connection with the strategic planning of natural resource management at the Finnish Forest and Park Service. Sindhu et al. [21] utilized hybrid strength-weakness-opportunity-challenges (SWOC)-AHP analysis to obtain the priority of the SWOC variables in the deployment of solar energy in India. SWOT-AHP method has also been adopted for exploring green hydrogen technology development and usage policymaking in Iran [22], identifying opportunities and barriers regarding public acceptance toward H2 stations in Korea and discussing possible strategies [23], or investigating the factors associated with each of the grey, blue, and green hydrogen production methods in the context of the shipping industry before prioritizing [24].

In Vietnam, several studies have focused on hydrogen energy, mainly on identifying the overall potential of hydrogen energy in the country's energy transition perspective, including hydrogen energy perspective, technologies, and development policies [25–27]. Phap et al. assessed the potential and the feasibility of producing GH2 from rooftop solar power systems in industrial parks in Vietnam [28]. In another case study [29], the authors evaluated the standalone solar hydrogen system for off-grid electrification in remote areas of Vietnam. Particularly, Duong et al. [30] investigated a perspective of Vietnam's power system toward the country's net zero target by specifically considering the possible GH2 conversion pathways for GTPPs. However, there is still a lack of research studies at the energy sector level that comprehensively address and evaluate specific factors impacting the GH2 conversion at GTPPs, which is one of the critical solutions to decarbonize Vietnam's power sector in the next decades.

In this paper, the SWOT analysis model is used in combination with the AHP method to explore and quantitatively evaluate the groups of strengths, weaknesses, opportunities, threats, and individual factors that influence the implementation of green hydrogen fuel conversion at Vietnam's GTPPs until 2050 toward the net zero target, and suggest appropriate strategies.

2. Materials and methods

2.1. Study method

In this study, the process of the SWOT-AHP combined method is proposed as illustrated in Figure 1.

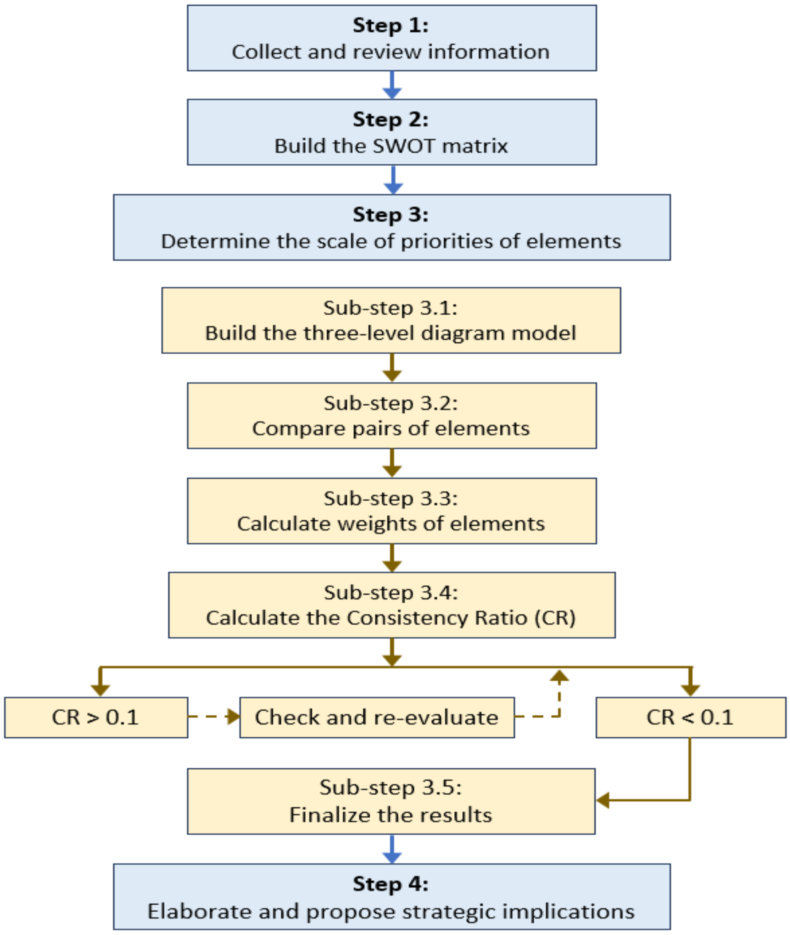

Figure 1. The proposed process of the SWOT-AHP method.

Specifically, the SWOT matrix content is converted into a hierarchical structure model with three levels (Figure 2), which allows an in-depth evaluation of various elements/factors of strengths, weaknesses, opportunities, and threats in the traditional SWOT matrix.

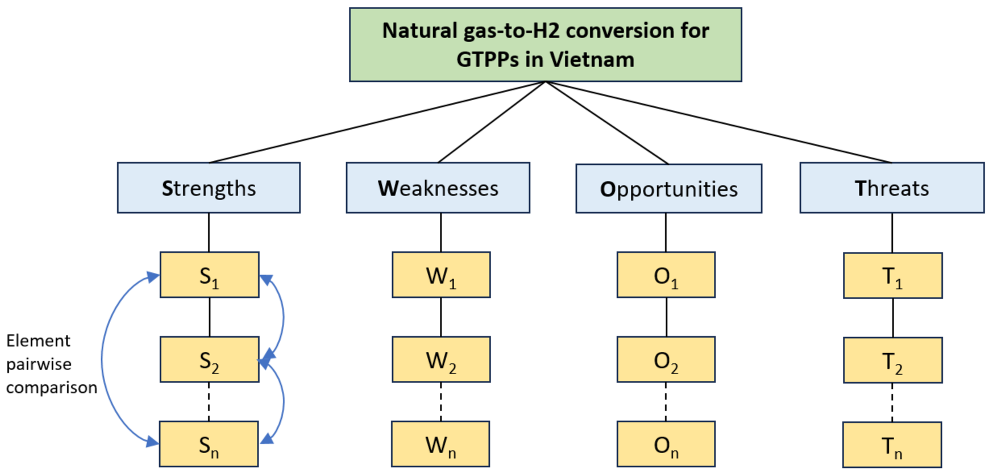

Figure 2. The analytical structure model.

The three levels of the hierarchical model include:

- Level 1: Describe the goal—GH2 conversion at GTPPs in Vietnam.
- Level 2: Describe four groups of influencing factors identified in the SWOT analysis (strengths, weaknesses, opportunities, threats)
- Level 3: Describe the influencing elements (or factors) of each group of S, W, O, T.

When applying the AHP method, the comparison between each pair of elements (i,j) in a level is elaborated and quantified using a quantitative scale significance assessment ranging from 1 (equal importance) to 9 (extreme importance) or the inverse of these values as described by Saaty RW in [10]. The n-level square matrix comprises relative weights of the factors (elements), which can be expressed as follows:

$$A_{ij} = a_{ij}/\Sigma a_{ij} \text{ (with } i,j = 1,\ldots,n) \quad (1)$$

The scale of priorities (or weights) for the elements is calculated by solving the principal eigenvector of the matrix and then normalizing the result as below:

$$w_i = a_{ij}/(n \cdot \Sigma a_{ij}) \quad (2)$$

Finally, the consistency ratio (CR) is determined to check for the consistency of evaluation. The value of CR is calculated according to the formula CR = CI/RI, where:

- CI (consistency index) = $(\lambda max - n)/(n - 1)$; in which λmax is the average value of the consistency vector.
- RI (random index) is the average value of CI. The RI value relates to the size of the comparison matrix.

The evaluation is considered acceptable with a value of CR lower than 0.1 [10,11].

The data sources for screening, determining, and analyzing the SWOT factors are derived from the energy master plans and energy development strategies of the countries, as well as a literature review of previous studies related to renewable energy and hydrogen energy. To develop the dataset for use in the AHP method, questionnaires were created to collect experts' opinions for comparison between elements/factors, with a total number of survey questionnaires of 16. Initially, the draft survey content was developed by the authors containing various factors of strength, weakness, opportunity, and threat determined in the previous step and then sent to a small group of experts for suggestion of proper content and comprehensibility. After receiving their feedback, the authors discussed and concluded the survey content accordingly before sending the questionnaires to all experts to get their feedback on the factor pairwise comparison and prioritization. The data processing and mathematical calculation according to the AHP method were carried out using the software AHP Priority Calculator [31] and the Excel spreadsheet. Based on the results from the SWOT-AHP model analysis and evaluation, strategic implications are proposed.

2.2. Analysis of the features of Vietnam's energy sector with regards to GH2 conversion perspective at GTPPs

2.2.1. Advantages and favorable aspects

- The country's abundant RE potential can be exploited to produce GH2 at a large scale

According to PDP8 [3], the technical potential of Vietnam's onshore wind power is approximately 221 GW, offshore wind power is approximately 600 GW (within the range of up to 200 km from the shore and at 100 m altitude), and the solar power is approximately 837 GW. These abundant potentials can be exploited to generate electricity for the national power system and produce GH2 to serve domestic needs such as GH2 conversion at GTPPs.

- The state’s strong orientation and policies

At COP26, Vietnam committed to bringing net emissions to zero by 2050. The country’s National Strategy on Climate Change then outlined the solutions to reduce GHG emissions, including the utilization of hydrogen energy [32]. The National Strategy for Energy Development oriented technological research and the development of some pilot projects and encouraged the use of hydrogen energy in accordance with the world's trends, including electricity production [1]. Vietnam’s Hydrogen Energy Development Strategy also anticipated the development and use of hydrogen energy to reduce GHG emissions in the energy sector, aiming at producing approximately 10–20 million tons/year by 2050 [2]. Specifically, the GTPPs are directed to implement fuel conversion to hydrogen when the technology is commercialized and the price is appropriate [3,33].

- International cooperation and support

Vietnam's green energy transition is strongly supported and committed by the international community through bilateral cooperation among several advanced countries and Vietnam via government-government frameworks or between organizations and businesses. Besides, there are also some multilateral cooperation mechanisms, such as JETP (Just Energy Transition Partnership), AZEC (Asian Zero Emissions Community, and VEPG (Viet Nam Energy Partnership Group), where Vietnam is an important partner.

- Large market potential

According to [3], a total capacity of approximately 32.4 GW of domestic gas and LNG-based power generation will be expected by 2050 to switch to using GH2, generating approximately 161.2–168.6 billion kWh per year. It is also estimated that the GH2 demand for fuel conversion at GTPPs in Vietnam by 2050 will be approximately 16 million tons per year, and green ammonia demand for fuel conversion of coal-fired power plants will be approximately 31–36 million tons annually [33]. This is a large market potential for investment, construction, operation, and trading activities related to the GH2 value chain.

- Opportunities for significant reduction of GHG emissions

Natural gas (NG)-based power generation can be considered a clean power source; CO_2 emissions from GTPPs (approximately 340 g/kWh) are much lower than coal-fired power sources (820 g/kWh) [34]. However, this emission is still considerable compared with RE sources. According to [35], the ability to cut CO_2 emissions when firing a GH2-NG (methane) mixture in a modern gas turbine unit is illustrated in Figure 3.

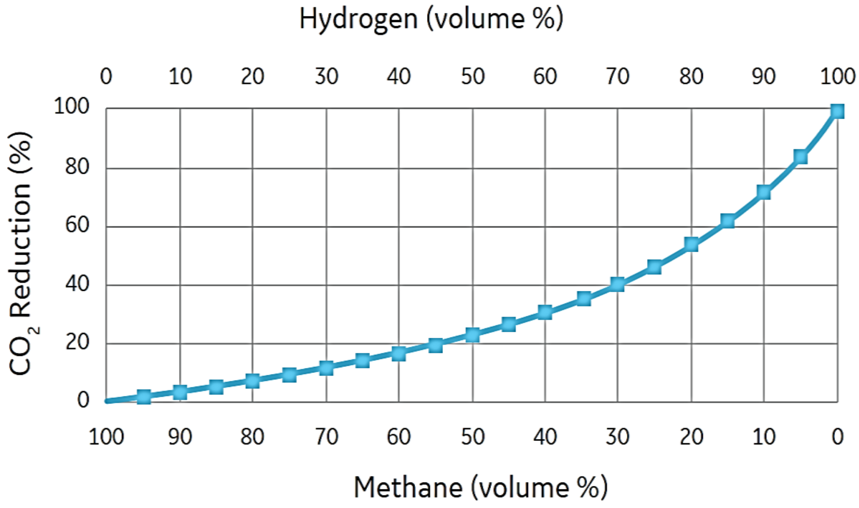

Figure 3. Relationship between CO_2 emissions and hydrogen/methane mixing ratios [35].

The potential of cutting CO_2 emission from mixing GH2 with NG at Vietnam's GTPPs is considerable. Just for LNG-based GTPPs (total capacity of approximately 25,400 MW by 2035), the reduction can be up to approximately 51.82 million tons CO_2 per year by 2050, as presented in Table 1.

Table 1. Estimation of CO_2 emission that can be cut by introducing GH2 to LNG-based GTPPs.

GH2 ratio in the mixture (%)	Period up to 2050	
	Corresponding capacity that burns GH2 (MW)	Volume of CO_2 that can be cut (mil. tons/year)
20	5,080	10.36
30	7,620	15.54
50	12,700	25.91
80	20,320	41.45
100	25,400	51.82

- Great chance to effectively use RE sources, ensuring energy security

According to PDP8 [3], the total installed capacity of Vietnam's power system will be approximately 150,489 MW by 2030, of which onshore wind power accounts for 14.5% (21,880 MW), offshore wind power achieves 4.0% (6,000 MW), and solar power reaches 8.5% (12,836 MW). Up to 2050, the total system capacity will reach 490,529–573,129 MW with the proportion of RE sources (excluding hydropower) increasing to 59.5%–63.8%. These planned capacity volumes are far lower than the country's abundant RE potential, so the remaining can be exploited to produce GH2. The authors have estimated the potential of RE that can be deployed to produce GH2 in Vietnam, as shown in Table 2.

Table 2. Estimation of GH2 volumes that can be produced from RE resources.

Description	Onshore wind power	Offshore wind power	PV solar power
Total technical potential (MW) [3]	221,000	600,000	837,485
Planned for power system development (MW) [3]	60,050–77,050	70,000–91,500	168,594–189,294
Maximum potential for GH2 production (MW)	143,950–160,950	508,500–530,000	648,191–668,891
Estimate of GH2 output (mil. tons/year)	7.20–8.05	33.90–35.33	16.20–16.72
Total GH2 output (mil. tons/year)	57.3–60.0		

Calculations by the authors with the following assumptions: capacity factor (full load operation) of PV solar power is 1,500 h/year, onshore wind power 3,000 h/year, offshore wind power 4,000 h/year, and the electricity consumption of the water electrolysis is 60 kWh/kg hydrogen.

In addition, in Vietnam's future power system with a high proportion of RE sources, excess electricity when RE sources are not mobilized or being curtailed (during off-peak times) can be used for hydrogen production to supply various energy storage needs, including for power generation.

- International integration, technology transfer in the GH2 value chain

Vietnam is in the industrialization and modernization era with rapid, sustainable economic growth. The country has great potential in developing the GH2 value chain and is a destination for many technology developers and equipment manufacturers in the RE industry in general and technological equipment for producing and using GH2 in particular. This is a great opportunity for the country to receive, use, and move toward mastering and developing core technologies in the GH2 value chain.

- Attract domestic and foreign investment

With abundant RE resources and great potential to develop the GH2 value chain, some GH2 production projects are being proposed or under development in Vietnam by foreign investors, with electricity sources from onshore wind power or a combination of onshore wind and solar power sources. The capacities of those facilities are from tens of thousands to several hundred thousand tons of hydrogen per year. In addition, more cooperation agreements are being established for the study and development of GH2 energy in Vietnam based on the large potential of offshore wind power. These are great potentials for international financing sources through bilateral and multilateral cooperation mechanisms.

2.2.2. Challenges and barriers

- Lack of infrastructure

Currently, most hydrogen in Vietnam is produced and used directly on-site in oil refineries and nitrogen fertilizer plants. As for gas pipeline infrastructure, there are systems distributed in the

Northeast, Southeast, and Southwest regions to transport NG from offshore gas fields to major consumers inland. So far, there has been no plan to upgrade or renovate the systems to receive hydrogen and handle hydrogen-NG mixing. Besides, most of the large-scale GTPPs using LNG are currently being developed using in-house unloading ports to receive and handle LNG without considering the possibility of hydrogen fuel [27]. Thus, Vietnam's infrastructure for the development of the GH2 value chain is almost non-existent, especially for electricity generation.

- Lack of specific mechanisms and policies to promote the production and use of GH2 for electricity generation

Many countries have introduced financial tools providing investment security for the hydrogen value chain to ensure feasibility and minimize financial risks for investment projects. Those include tax incentives, a contract for difference (CfD) mechanism, direct subsidies, direct financial support for the development of production and manufacturing technologies, or minimizing administrative procedures for investment projects [36].

Although there have been major orientations and macro-level policies for energy transition, RE, and GH2 energy development [1–3,33], Vietnam currently lacks specific and feasible mechanisms and policies to realize and promote the development of the GH2 value chain.

- The absence of regulations, norms, and standards

According to IEA [36], many regions (mainly developed countries, the European Union, and China) and the ISO have established or are actively developing regulations and standards for hydrogen production from renewable electricity and low-emission sources, as well as for safety, technology compatibility, and operations related to the storage and transportation of hydrogen, hydrogen-fueled vehicles, fuel cells, and the blending of hydrogen in natural gas pipelines. In contrast, Vietnam currently lacks a development plan for formulating and completing these standards and regulations.

- Incapability in mastering core technologies

As a developing country, Vietnam does not yet have or master the core technologies in the value chain such as hydrogen production using water electrolysis technology, massive hydrogen storage/transportation, or hydrogen energy utilization technologies (fuel cells, gas turbines, etc.). To be proactive and avoid dependence on international supply and market fluctuations, Vietnam needs to approach and gradually master technologies for securing hydrogen supply, including RE development, storing, transporting, and supplying hydrogen. Vietnam Is planning to fully acquire and master advanced technology in GH2 energy production by 2050 [2].

- Hydrogen-fired gas turbine technology is still under development, not yet mature/commercialized

Recently, most gas turbine manufacturers worldwide have announced the ability to handle a mixture of at least 30%–50% hydrogen (by volume), and a few have declared the ability to burn 100% hydrogen in some new commercial gas turbine lines [34,35,37,38]. This is confirmed by some energy agencies and organizations in developed countries [39–41]. Regarding practical applications, currently, a number of new GTPP projects are being built with gas turbine equipment having a "hydrogen ready" feature, and some other existing plants are being upgraded/renovated to convert to hydrogen [42–46], revealing notable achievements in the process of technology commercialization.

As for technology readiness level (TRL) according to the 11-level scale of the IEA, gas turbine technology is evaluated as being able to handle a hydrogen-rich mixture (hydrogen content of 50%–60%) at level 9/11 (commercial operation in relevant environment), while 100% hydrogen is at level 7/11 (pre-commercial demonstration). Besides, the TRLs of some stages in the hydrogen value chain (massive storage and transport) are also not yet completed and commercialized [36,47].

- GH2 price is still expensive, leading to high electricity production cost

The current cost of producing GH2 globally is still high at 4–8 USD/kg; therefore, it is difficult to compete with other traditional energy sources. Along with the long-term decreasing trend of RE electricity prices, GH2 prices are expected to continue to drop, especially in areas with ample potential for RE. The price of GH2 by 2030 and 2050 is expected to decrease to approximately 1.5–5 USD/kg and 1–3 USD/kg, respectively, varying according to different regions of the world and with different scenarios regarding the cost of electrolysis equipment [36,48–50]. In Vietnam, the production cost of GH2 using electrolysis technology with electricity supplied from wind and solar power plants in the South of Vietnam can be up to 6.5–11.0 USD/kg depending on different combinations of RE sources. By 2050, this cost is expected to decrease to 1.5–2.5 USD/kg, which is in range with the world perspective [51].

The authors have estimated the levelized cost of electricity (LCOE) (in Uscent/kWh) at a typical modern 1,500 MW LNG-based GTPP for various cases of GH2 price and blending ratio on the fuel mixture. The result indicates that the high GH2 price has a great impact on the LCOE, as can be seen in Figure 4. With lower GH2, e.g., 2–3 USD/kg, the LCOE is quite stable and can compete in the power system (according to PDP8's estimation, the average electricity generation cost of the system in the period 2030–2050 will range from 11.7 to 13.2 Uscent/kWh [2]).

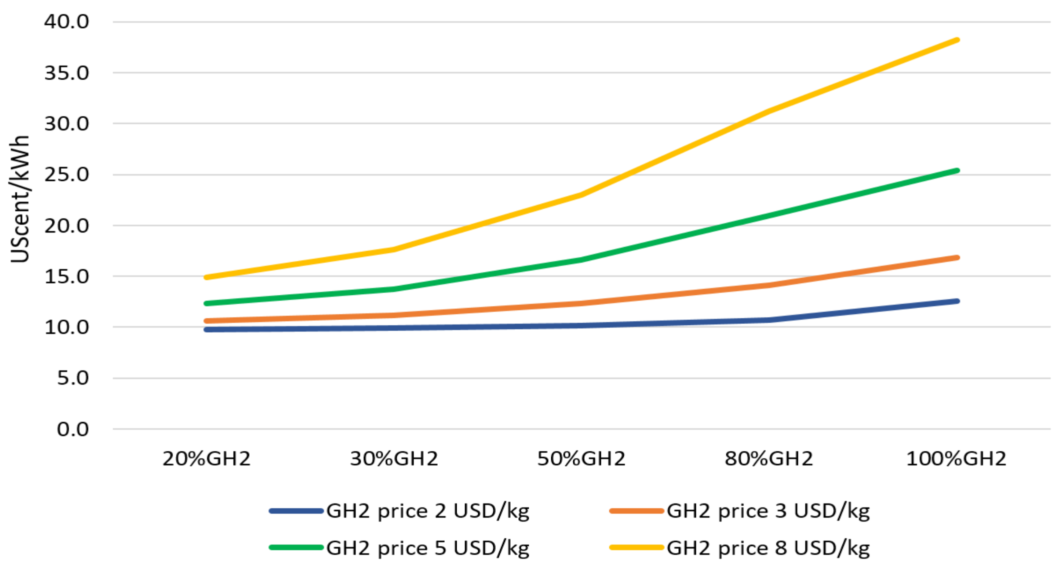

Figure 4. The impact of GH2 price and mixing ratio on GTPP's LCOE.

Regarding the cost of transportation, a study indicates that for distances up to 3,000 km, transporting compressed hydrogen may be the cheapest option, especially in the case of using pressurized pipes (approximately 0.5–1.0 EUR/kg). In longer distances, liquefied hydrogen and LOHC are likely the lowest-cost options. At distances above 16,000 km, LOHC and ammonia may be the preferred choice [52].

- Lack of investment capital for GH2 fuel conversion

According to a World Bank report [53], Vietnam may need up to 368 billion USD in the period of 2022–2040 to build resilience and achieve decarbonization. In particular, the total financial need for the decarbonization effort is estimated to be 114 billion USD in the same period.

As mentioned above, GH2 can be produced domestically using RE sources such as wind or solar power, or imported if the price is competitive. In any case, it is necessary to develop a comprehensive infrastructure to receive, store, transport, and supply hydrogen to consumers. The cost for the GH2 value chain with the above demand will possibly be up to hundreds of billions of dollars. This is a very massive capital need that will require mobilizing both domestic and foreign investment resources through various effective cooperation mechanisms.

- Shortage of specialized human resources

The energy transition process will have a significant impact on the workforce operating in the traditional energy industry in Vietnam. Existing human resources in traditional fields (oil, gas, coal, etc.) will be negatively impacted due to decreasing demand, while the need for highly skilled human resources to work in the field of RE and new energy is expected to increase significantly. Hydrogen energy and the GH2 value chain are still very new, meaning that Vietnam lacks human resources with experience and expertise in this field, particularly for hydrogen-fired gas turbine systems.

3. Results

3.1. Identification of the influencing elements

The identification of the factors (elements) of strengths, weaknesses, opportunities, and threats influencing the GH2 conversion at GTPPs are summarized as shown in Table 3.

The square matrices to compare and evaluate the level of importance (weight) between each pair of elements for each group of factors (S, W, O, T) are then formulated using the study method as described. The results of the weight of the elements for each group are shown in Figures 5 and 6.

Table 3. Compiled list of the factors influencing GH2 conversion at GTPPs in Vietnam.

Groups of elements	Elements	Remark
Strengths (S)	Abundant potential of RE	S1
	The state's orientation and policy	S2
	International collaboration and support	S3
	Large market potential	S4
Weaknesses (W)	Lack of infrastructure	W1
	Lack of specific incentive mechanisms and policies	W2
	Absence of regulations, norms, and standards	W3
	Incapability in mastering core technologies	W4
Opportunities (O)	Reduce GHGs emissions	O1
	Develop and effectively use RE, ensuring energy security	O2
	International integration and technology transfer in the GH2 value chain	O3
	Attract domestic and foreign investment	O4
Threats (T)	Technology not yet mature/commercialized	T1
	High electricity production cost (due to the high price of GH2)	T2
	Lack of investment capital	T3
	Shortage of specialized human resources	T4

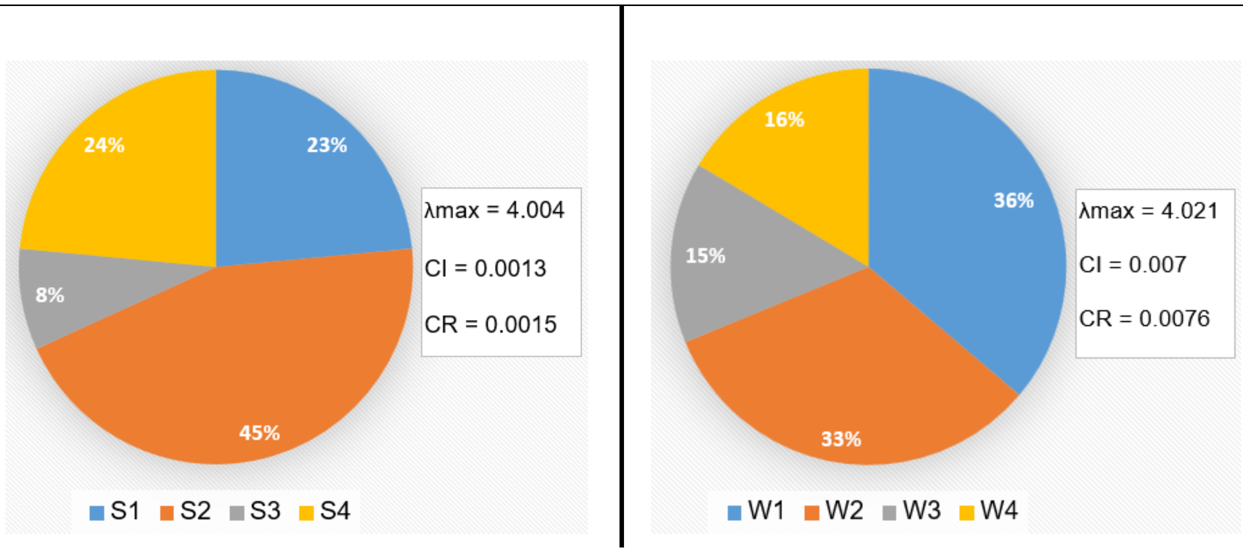

Figure 5. Weight evaluation of the strength (S) and weakness (W) elements.

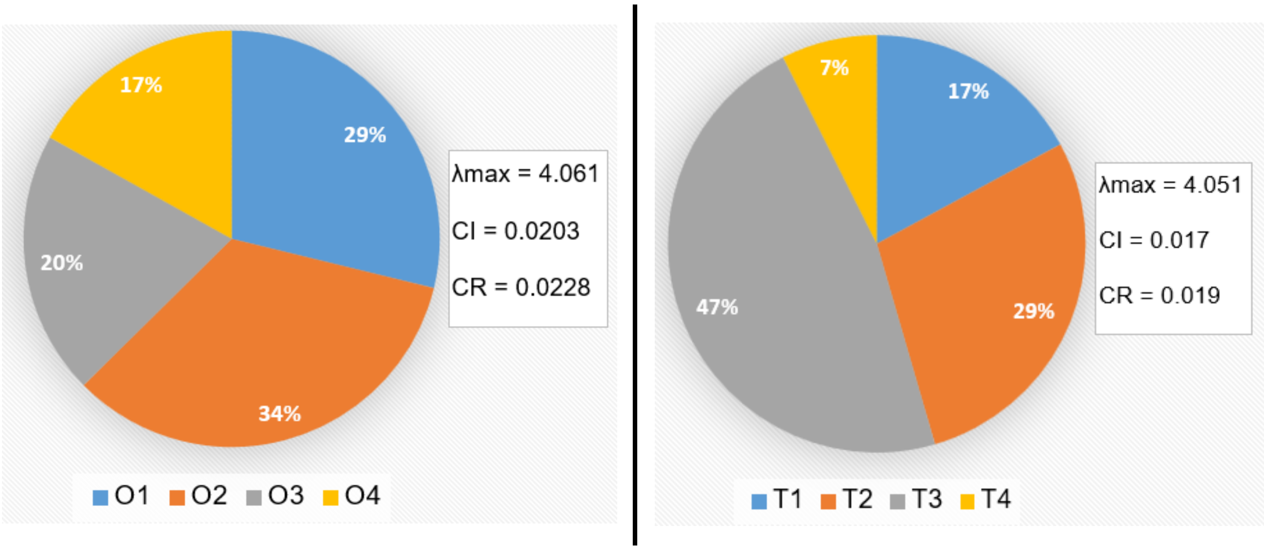

Figure 6. Weight evaluation of the opportunity (O) and threat (T) elements.

Next, the weighing of the groups of strengths, opportunities, weaknesses, and threats is implemented as shown in Figure 7.

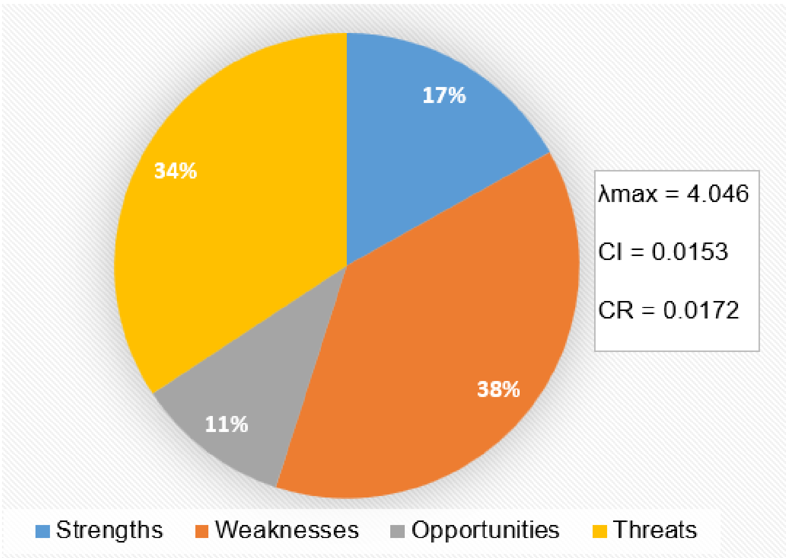

Figure 7. Weight evaluation of the groups.

Finally, the weight evaluation matrix of the groups and element factors is formulated and summarized as shown in Table 4.

Table 4. Summary of overall weight evaluation.

Groups	Weight of group (GW)	Element	Weight of element in group (EW)	Global weight of element (EGW)	Group ranking	Global ranking	Consistency ratio
Strengths (S)	0.169	S1	0.235	0.040	2	9	0.0015
		S2	0.446	0.075	1	5	
		S3	0.082	0.014	4	16	
		S4	0.235	0.040	2	9	
Weaknesses (W)	0.381	W1	0.362	0.138	1	2	0.0076
		W2	0.326	0.124	2	3	
		W3	0.148	0.056	4	8	
		W4	0.163	0.062	3	6	
Opportunities (O)	0.108	O1	0.288	0.031	2	12	0.0228
		O2	0.338	0.037	1	11	
		O3	0.205	0.022	3	14	
		O4	0.169	0.018	4	15	
Threats (T)	0.343	T1	0.171	0.059	3	7	0.0191
		T2	0.284	0.097	2	4	
		T3	0.471	0.162	1	1	
		T4	0.074	0.025	4	13	

4. Discussion

4.1. Comments

According to the analysis and evaluation results presented in sections 2 and 3, at the level of groups, the most influencing one is *Weaknesses* with the highest weight (GW = 0.381), followed by the group *Threats* (GW = 0.343). The remaining groups of factors (*Strengths* and *Opportunities*) have much lower weights, showing that their influence is not very significant. This is logical because Vietnam is a developing country, and energy demand for economic development continues to increase while having to swiftly reduce emissions. Therefore, the country's energy transition ambitions will definitely face significant barriers and challenges such as a lack of resources and capability, high cost of technologies, imperfect legal framework, etc.

At the level of elements, in the *Weaknesses* group, the element W1 "lack of infrastructure" has the greatest influence, with an EW of 0.362, suggesting that the GH2 conversion at GTPPs relies heavily on the availability of the GH2 infrastructure systems. The second element is W2 "lack of specific incentive mechanisms and policies" with EW = 0.326. This is also logical, as Vietnam presents a great potential for RE that is almost unexploited. Thus, mechanisms and legal framework/policies promoting and ensuring viable implementation are very important and shall be in place to unlock the large-scale deployment of RE sources in order to efficiently produce GH2.

In the group of *Threats*, the element T3 "lack of investment capital" has the greatest influence, with an EW of 0.471. This accurately reflects the current situation in Vietnam. Up to now, Vietnam has been among the countries with a leading RE development rate and has attracted large investment resources both domestically and internationally. Nevertheless, to achieve energy transition in general and fuel conversion at GTPPs in particular, continued huge investment resources are needed. Other challenges of GH2 cost and immature technology are common problems not only for Vietnam but also for other countries; nevertheless, these problems can likely be solved in the medium and long term according to current development trends in the world.

Regarding the group *Strengths*, element S2 "State's orientation and policies" is the most important with an EW of 0.446. After its declaration at COP26, the Vietnam government created a number of policies, strategies, and national plans for developing the energy and power sector, with priority given to strongly developing RE, electrifying many energy-using fields, and directing the conversion of coal and gas-fired power plants to use biomass, GH2, and green ammonia. The elements S1 "good RE potential" and S3 "international collaboration and support" are also considerable, both with EWs of 0.235.

As for *Opportunities*, the EWs of the elements are relatively equal. The element O2 "develop and effectively use RE, ensuring energy security" has the highest influence, with an EW of 0.338, followed by the element O1 "reduce GHG emissions". This is clear since overcoming the challenges and promoting the above-mentioned strengths will allow opportunities to develop and effectively use RE, leading to a reduction of GHG emissions. Further, a large clean energy market will attract investment from both domestic and foreign sources, further promoting green energy transition.

Finally, considering the overall level of influencing degree, the top four elements include T3 "lack of investment capital", W1 "lack of infrastructure", W2 "lack of specific incentive mechanisms and policies", and T2 "high electricity production cost" with EWGs ranging from 0.097 to 0.162. These all belong to the *Threats* and *Weaknesses* factors, revealing that barriers and challenges are the most significant factors for the country considering its effort toward a green energy transition in general and GH2 conversion at GTPPs in particular.

4.2. Strategic implications

Based on the calculations, analysis, and evaluation presented above, some strategic implications are proposed.

Strategy S-T: Take advantage of internal strengths to avoid/limit external threats.

ST1: The government continues to promote its role in guiding policies on energy transition and fuel conversion, calling for collaboration and support from the international community to attract technology transfer and investment capital; building legal frameworks, mechanisms, and feasible incentives to strongly support the development of RE, hydrogen energy, and fuel conversion.

ST2: Strongly develop RE sources with the government's leading role in infrastructure development and preferential policy mechanisms to reduce costs of GH2 production, storage, and transportation. The falling price of GH2 along with incentive mechanisms to promote the use of hydrogen energy in the economy, including GH2 conversion at GTPPs, will create growing market demand. When market demand develops, it will have a positive effect on the GH2 value chain to increase.

Strategy S-O: Make the most of strengths to exploit opportunities.

SO1: Exploit, develop, and effectively use Vietnam's abundant RE potential to ensure energy security and supply electricity for GH2 production to meet the needs of energy transition, reducing GHG emissions.

Strategy W-O: Minimize weaknesses to take advantage of opportunities.

WO1: Develop and promulgate favorable policies/mechanisms to attract domestic and foreign investment sources for the development of RE sources, GH2 value chain, and GH2 conversion at GTPPs. Vietnam can obtain international experience in facilitating incentives and risk reduction mechanisms for investment projects in the value chain such as tax incentives, CfD, direct price subsidies, carbon market, etc.

WO2: Consult and learn from international experience to develop a comprehensive system of regulations and standards on hydrogen energy suitable to Vietnamese conditions and in harmony with the world, facilitating investment and use of hydrogen energy.

WO3: Making joint venture/cooperation with international technology companies to facilitate the transfer of core technologies such as water electrolysis and large-volume hydrogen storage and transportation; localization of the processes that Vietnam can do in the design, manufacturing, construction, and installation, and O&M.

Strategy W-T: Diminish weaknesses to limit threats.

WT1: The high price of GH2 remains a major challenge to developing this new energy. Thus, Vietnam needs to develop strategies to reduce the cost of RE for GH2 production as well as the investment costs of electrolysis plants, such as (i) promulgating tax incentive mechanisms, (ii) introducing special power trading mechanisms like DPPA, CfD, etc., and (iii) promoting technology transfer and mastering and localizing core technologies and equipment manufacturing.

5. Conclusions

This study uses the combined SWOT-AHP analysis method to quantitatively evaluate the influence of the factors (strengths, weaknesses, opportunities, challenges) on the goal of GH2 conversion in the GTPPs. Research results reveal that among the groups of factors, the most significant one is *Weaknesses* (group weight = 0.381), followed by *Threats* (0.343), *Strengths* (0.169), and *Opportunities* (0.108). At the level of element factors, the lack of infrastructure (factor's overall weight = 0.138) and the insufficient legal framework and incentive mechanism (0.124) are the biggest weaknesses, while the state's consistent orientation and policies (0.075) and the abundant potential of RE resources (0.04) are Vietnam's noticeable strengths. Besides, the opportunities for Vietnam are also quite clear, such as effectively using available resources (0.037) and reducing GHGs (0.031), while the main challenges include a lack of capital resources (0.162) and high GH2 prices (0.097).

By knowing the important levels of the influencing factors, a set of strategic solutions can be developed and expedited by the country to meet the expected goal, including (i) perfecting the legal framework on RE development, especially for offshore wind power, and GH2 energy with appropriate and stable incentive mechanisms to strongly attract private and foreign resources, (ii) introducing favorable policies to mobilize investment resources to efficiently develop infrastructure systems serving for GH2 production, transport, and utilization, (iii) setting a clear GH2 conversion roadmap for GTPPs with specific expected targets and related supporting regulations as necessary, and (iv) strengthening international collaboration on sharing information and knowledge, technology transfer, capacity and human resource building, etc.

This study contributes to improving the knowledge of the specific situation of a developing country (Vietnam) aiming for a green energy transition in general and hydrogen conversion at fossil-fueled power plants in particular. The output of the study can be useful for policymakers, GTPP owners, and investors, as well as relevant stakeholders who are working in various areas of the energy transition process, not only in Vietnam but also in other countries with similar situations.

In conducting the study, only experts in the field of energy policy and renewable energy were interviewed to give opinions on the evaluation and comparison of the relevant factors. The detailed considerations for each GTPP in terms of specific site conditions and technological and economic performance relating to GH2 conversion are also not covered due to limitations in time and resources. Further research on this subject may be worth inviting feedback from more experts on wider fields like fossil-fueled power technology, energy economics, environmental protection, etc., and considering more specific techno-economic aspects of the GTPPs. Besides, future studies can also address other essential aspects relating to GH2 conversion, such as specific mechanisms for sustaining GH2 production from RE sources, electricity pricing, and CO_2 pricing policy for power plants that shift to use GH2.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, Duong Doan Ngoc and Kien Duong Trung; methodology, Kien Duong Trung and Phap Vu Minh; software, Thao Nguyen Van and Duong Doan Ngoc; data analysis, Thao Nguyen Van; writing—original draft, Duong Doan Ngoc and Thao Nguyen Van; writing—review and editing, Phap Vu Minh; All authors have agreed to the published version of the manuscript.

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