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Research Article

SWOT-AHP Analysis of Different Colours of Hydrogen for Decarbonization of Shipping

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Abstract

Maritime transportation has experienced significant growth since 1990, with its use surging by over 150%, constituting approximately 90% of global transportation for goods transfer. However, the overwhelming majority of the global maritime fleet still relies heavily on fossil fuels, leading to substantial greenhouse gas (GHG) emissions. To address these challenges, the International Maritime Organization (IMO) has implemented regulations and initiatives to mitigate CO_2 and GHG emissions from shipping. Among these, the use of hydrogen emerges as a promising option for achieving sustainable decarbonization of maritime transportation. This paper investigates grey, blue, and green hydrogen production methods in the context of the shipping industry. Through strength, weakness, opportunity, and threat (SWOT) analysis combined with Analytic Hierarchy Process (AHP) methodology, the strengths, weaknesses, opportunities, and threats associated with each hydrogen type are prioritised and evaluated. The findings reveal nuanced shifts in strategic considerations during transitions between hydrogen types, highlighting the importance of regulatory support and technological advancements in driving the transition towards cleaner hydrogen production methods. The study concludes by emphasizing the need for strategic planning and technological advances to overcome challenges and capitalize on opportunities for a more sustainable and resilient energy future in maritime transportation.

Keywords: Decarbonization, Hydrogen, Marine Engineering, Maritime Transportation, SWOT-AHP

Introduction

Since 1990, the use of maritime transportation has surged by over 150% (Baldi et al., 2020), constituting approximately 90% of global transportation for goods transfer (Inal et al., 2022). Despite being an efficient means of transportation for goods and passengers, the overwhelming majority of the global maritime fleet still operates using internal combustion engine propulsion systems, relying heavily on fossil fuels (Rattazzi et al., 2021). According to the International Maritime Organization (IMO), the maritime sector consumes approximately 300 million tons of fossil fuels annually (IMO, 2021). Among these, heavy fuel oil (HFO) accounts for roughly 72%, marine diesel oil (MDO) for 26%, and liquefied natural gas (LNG) for 2% (Gray et al., 2021). This heavy reliance on fossil fuels has led to a notable increase in total greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane, and nitrous oxide, from 977 million tons to 1,076 million tons, with CO_2 emissions rising from 962 million tons to 1,056 million tons between 2012 and 2018 (IMO, 2020). Consequently, maritime transportation is responsible for approximately 3.1% of global CO_2 emissions, ranking as the sixth-largest emitter worldwide (Balcombe et al., 2019). Projections from the IMO suggest that CO_2 emissions from maritime transportation could surge by 50% to 250% by 2050 without effective mitigation strategies (Rivarolo et al., 2020).

In response to these challenges, the IMO has been actively pursuing measures to mitigate CO_2 and GHG emissions from shipping. One key regulation is the Regulations on Energy Efficiency for Ships, which came into effect on January 1, 2013. This regulation introduced mandatory terms such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), as well as a voluntary term known as the Energy Efficiency Operational Indicator (EEOI) (IMO, 2021). The EEDI applies to newly built ships and promotes the use of energy-efficient materials and technologies by setting limits on the index value for new vessels. Conversely, the SEEMP is required for existing ships and includes operational energy efficiency measures tailored to each vessel. The EEOI, meanwhile, provides a voluntary index to assess voyage efficiency based on CO_2 emissions per cargo-carrying work. Additionally, the IMO implemented a Data Collection System on March 1, 2018, to record the annual voyage-based CO_2 emissions of ships larger than 5000 GRT engaged in international voyages (IMO, 2021). In 2018, the IMO unveiled its Initial Greenhouse Gas Strategy, outlining dual objectives for maritime transport (IMO, 2018). The first objective aims to reduce CO_2 emissions per transport work by at least 40% by 2030 and 70% by 2050, compared to 2008 levels. In order to achieve a fulfilment of the related aim, biofuels are regarded as a transitional fuel source for maritime use in the short and medium term (Sevim and Zincir, 2022a, 2022b, 2023). The second objective seeks to cut GHG emissions from maritime transportation by 50% below 2008 levels by 2050. To achieve these targets, the strategy delineates candidate measures categorized into short-term (2018-2023), medium-term (2023-2030) and long-term (2030 onwards) time frames. These measures span operational, market-based, policy-based, and technology-based domains, allowing for flexibility in implementation. Notably, alternative fuel usage emerges as a common candidate measure across all terms of the strategy, with a gradual transition from low-carbon to zero-carbon alternatives envisioned over time. Among these alternatives, hydrogen emerges as a promising option for achieving complete decarbonization of maritime transportation, offering zero carbon content (Inal and Deniz, 2018; Zincir, 2020).

The aforementioned IMO initiatives serve as a crucial foundation for addressing CO_2 and GHG emissions in shipping. By gradually transitioning from low-carbon to zero-carbon fuels the maritime sector aims to achieve zero-carbon shipping ((Balcombe et al., 2019; Hoang et al., 2023; Inal et al., 2022). Furthermore, renewable energy sources such as solar and wind energy are assessed. Through preliminary evaluation, hydrogen types are compared to determine the optimal fuel option, paving the way for a discussion on sustainable decarbonization and the transition toward zero-carbon shipping. Hydrogen is considered a promising fuel for the maritime industry with its zero-carbon chemical structure (Atilhan et al., 2021; Johnston et al., 2022). Despite the high gravimetric energy density of hydrogen in liquid form, hard storage conditions onboard ships seem as the major obstacle to expanding its area of use (Depken et al., 2022; Van Hoecke et al., 2021). On the other hand, reaching zero-carbon from well to wheel by using renewable energy is attractive to invest in hydrogen technologies (Mallouppas and Yfantis, 2021).

In this manuscript, hydrogen types are investigated according to the production process to use in the shipping industry. Although there are several types of production methods, grey, blue, and green hydrogen types are summarized in Section 2. Section 3 presents the methodology SWOT-AHP method for decision-making in short, mid, and long terms. Section 4 discusses the results and lastly, Section 5 concludes the paper.

Hydrogen Types

Hydrogen can be produced from various primary energy sources, and its costs and emissions vary significantly depending on the production method and type of energy used (Incer-Valverde et al., 2023). This variability is why hydrogen production technologies are often categorized by different colours, such as grey, blue, turquoise, green, purple, and yellow, as can be observed in Figure 1. In this study, however, only grey, blue, and green hydrogen were considered as the primary analysis subjects.

Grey Hydrogen

Grey hydrogen is produced from fossil fuels, mainly natural gas (CH4). Grey hydrogen refers to hydrogen produced through methods such as steam methane reforming, partial oxidation, or autothermal reforming (Arcos and Santos, 2023). In this process, methane reacts with high-temperature steam in the presence of a catalyst to produce hydrogen and so, carbon monoxide. Presently, the majority of hydrogen production falls under the category of grey hydrogen. It is noteworthy that 40% of grey hydrogen is a by-product of other chemical processes. Primarily, grey hydrogen is useful in the petrochemical industry and ammonia production. Approximately 6% of globally extracted natural gas and 2% of coal are utilized in the production of grey hydrogen. However, the chief drawback of grey hydrogen is its high carbon dioxide (CO_2) emissions during production, amounting to approximately 830 million metric tons of CO_2 per year. Grey hydrogen is the most common hydrogen production technique compared to other colours because of its higher technological maturity. This makes it less environmentally friendly because of the carbon released during the production process.

Blue Hydrogen

Blue hydrogen is a captivating alternative for low-carbon hydrogen production. It involves generating hydrogen from fossil fuels and incorporating a carbon capture, utilization, and storage (CCUS) system. Utilization of captured carbon is not decisive for blue hydrogen classification; however, it is worth noting that as an option. Carbon capture and storage (CCS) technology is employed to capture CO_2 emissions from the hydrogen production process and store them underground, typically in geological formations, to prevent them from entering the atmosphere (Lubbe et al., 2023). The coupled carbon capture system during blue hydrogen production can allow for the continued use of fossil fuels while reducing the carbon footprint. Because blue hydrogen originates from fossil fuels, it has lower costs than the green type.

Blue hydrogen offers a significant reduction in carbon emissions compared to grey hydrogen, as the captured CO_2 is prevented from entering the atmosphere. However, it still relies on natural gas, making it a transitional solution toward decarbonization rather than a completely clean energy source.

Green Hydrogen

Green hydrogen is hydrogen that's produced through a process called electrolysis, which uses electricity to split water molecules into hydrogen and oxygen. The key here is that the electricity used in this process comes from renewable sources like solar, wave, or wind power. This means that producing green hydrogen doesn't create any greenhouse gas emissions, unlike other methods of hydrogen production that rely on fossil fuels. For this reason, green hydrogen is often called "clean hydrogen" or "renewable hydrogen" (Ngene et al., 2014; Schuler et al., 2023). Green hydrogen is a promising solution to reach zero-carbon sustainable energy production and so, the maritime transportation industry. However, there are still some challenges that need to be addressed before green hydrogen can become widely used. Unfortunately, with current industrial approaches, green hydrogen constitutes only a small portion of the total hydrogen production because of the high investment costs during the production process. Nevertheless, it draws a promising future trajectory as the cleanest form of hydrogen, crucial for fulfilling net-zero carbon goals. It seems that in case of cost reduction in the electrolysis process, this technology advances into a viable option.

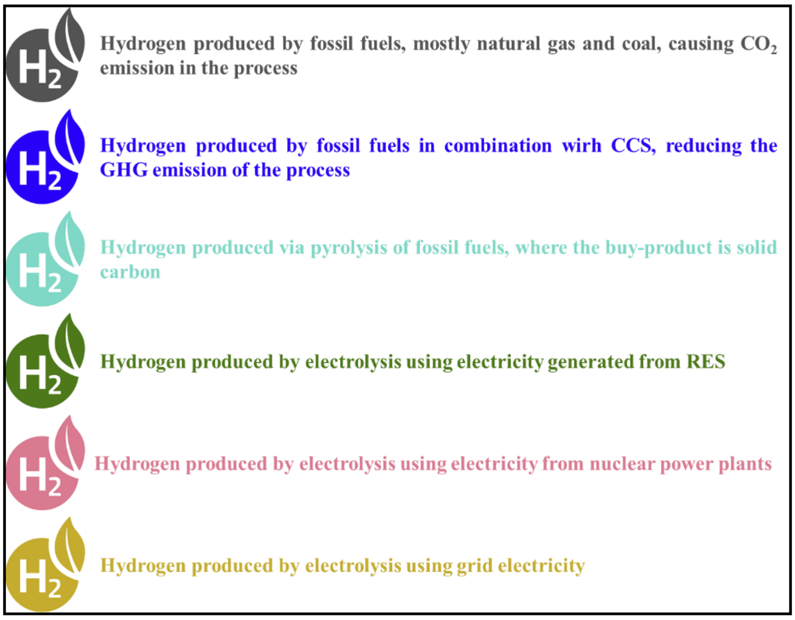

Fig. 1. Colours of hydrogen (Ajanovic et al., 2022)

SWOT Analysis

A SWOT analysis, a fundamental instrument utilized by organizations, serves as strategic planning tool to qualitatively identify and evaluate their internal strengths and weaknesses, as well as external opportunities and threats. It was first proposed by George Albert Smith Jr. and C Roland Christensen, professors of Harvard Business School in the early 1950s (Chang and Chow, 1999; Chermack and Kasshanna, 2007). The concept of strengths and weaknesses pertains to factors that can be influenced by the system itself, encompassing aspects such as resources, capabilities, and internal processes. Conversely, opportunities and threats represent external variables that may impact the system and any organization, encompassing market trends, competition, regulatory changes, and economic conditions. The implementation of a SWOT analysis enables to gain of a comprehensive overview of the present situation, facilitates informed decision-making processes, and formulates effective strategies to optimize the strengths, address the weaknesses, seize opportunities, and mitigate threats. Figure 2 indicates some key questions for identifying the related aspects of a system. Benzaghta et al. (2021) conducted an extensive literature review focusing on SWOT analysis, categorizing the studies into five primary domains: general management, education, marketing, healthcare, and agriculture. In their investigation, they scrutinized a total of 17 manuscripts, referred to as "key papers," which delve into SWOT analysis and enhance its utility through the integration of various quantitative methodologies.

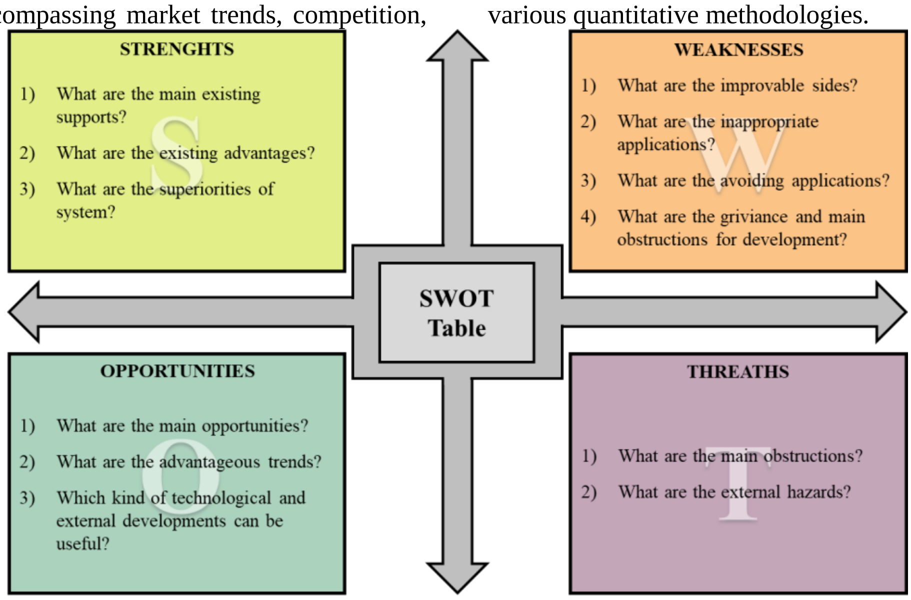

Fig. 2. Key questions for SWOT analysis

In addition to the aforementioned five primary domains, for the purpose of aiding in strategic decision-making and planning the new systems, SWOT analysis is frequently employed technique in the fields of environmental studies, information technologies, tourism, supply chain, and so forth (Alabool, 2023; Celik et al., 2024; SORMAZ et al., 2023; Wahab et al., 2023). Moreover, in the maritime transportation industry, the SWOT analysis approach is a widely used methodology to assess internal and external dynamics, facilitating the development of strategic plans, including initiatives such as carbon capture, storage, and transportation, decarbonization efforts, autonomous shipping, and Arctic navigation (Şahin et al., 2014; Şenol et al., 2017; Zincir et al., 2023). In general, expert groups can be divided into two categories: homogeneous, comprising experts from the same field of interest, and heterogeneous, comprising experts from different fields.

In this study, a heterogeneous expert group was established, comprising an academician, a naval architecture, a marine engineer, an oceangoing master and a ship owner. Total 5 field experts were consulted for constituting the SWOT aspects given in Table 1 and conducting pairwise comparisons of AHP methodology.

Analytic hierarchy process (AHP)

AHP is a technique for the structured analysis of complex decision-making processes, developed by Thomas L. Saaty (1980). It is designed to assist decision-makers by enabling the structuring of a problem into a hierarchy of criteria and alternatives and then enabling the structured evaluation and prioritization of these elements based on pairwise comparisons and mathematical calculations. AHP enables decision-makers to quantify both tangible and intangible factors, determine their relative importance, and arrive at a rational decision that reflects their preferences and objectives.

Table 1. SWOT analysis for grey, blue, and green hydrogen

	Grey Hydrogen	**Blue Hydrogen**	**Green Hydrogen**
Strengths	**S1**-Established infrastructure	**S1**-Emissions reduction with CCS technology	**S1**-Zero emissions
	S2-Cost efficiency compared to other types	**S2**-Potential for technological advancements in CCS (carbon capture system)	**S2**-Renewable energy integration
	S3-Familiarity and reliability	**S3**-Transitional fuel to decarbonization	**S3**-Utilizes abundant renewable energy sources
	S4-Integration flexibility via different production options	**S4**-High variety of feedstocks	**S4**-Aligns with global sustainability objectives
Weaknesses	**W1**-High carbon emissions during production	**W1**-Dependent on CCS technology onboard ships	**W1**-High investment requirement for infrastructure
	W2-Environmental concerns exist	**W2**-Dependent on fossil fuels	**W2**-High cost
	W3-Limited sustainability	**W3**-CCS sourced reliability troubles	**W3**-Relatively low production capacity
	W4-Well to wheel emissions regulative risks	**W4**-Carbon capture system-based scalability onboard ships	**W4**-Dependent on renewable energy at the port side
Opportunities	**O1**-Possible strategies developments towards cleaner alternatives	**O1**-Regulatory support and incentives for CCS	**O1**-Regulatory incentives for renewable energy projects
	O2-Investment in carbon capture technologies	**O2**-Collaborative partnerships for technological advancements	**O2**-Technological advancements in electrolysis technology
	O3-Strongest option in short term	**O3**-Advancement at the CCS poses great opportunities to extent the investment	**O3**-Port and ship collaboration in terms of renewable hydrogen storage
Threats	**T1**-Regulatory compliance challenges	**T1**-Regulatory uncertainty regarding emissions regulations	**T1**-Infrastructure constraints
	T2-Market competition from cleaner fuel options	**T2**-Market competition from alternative fuels	**T2**-Competition from alternative propulsion technologies
	T3-Environmental concerns still exist	**T3**-Technological and operational challenges considering carbon capture technology	**T3**-Renewable energy using hydrogen bunkering options

The technique is employed extensively in a multitude of domains, including business, engineering, healthcare, public policy, supply chain management, and others (Dehghanimohammadabadi and Kabadayi, 2020; Kostić-Ljubisavljević and Samčović, 2024; Rabia and Bellabdaoui, 2023; Sha and Liu, 2022; Zekhnini et al., 2021). Khan and Ali (2020) conducted a comprehensive analysis of 920 articles that employed AHP and ANP methodologies. Their findings indicate that AHP is a highly preferred decision-making method in nearly every field where multi-criteria decision-making is a challenge. In the maritime transportation industry, the AHP method is frequently employed for the resolution of multi-criteria decision-making problems. These include navigation management, port management, technology selection, autonomous operations, and maritime economics (Bolat et al., 2020; Kim and Mallam, 2020; Sahin and Senol, 2015; Sahin et al., 2015; Yang et al., 2020).

In this study, SuperDecisions (www.superdecisions.com) software was utilized for performing AHP analysis of the predetermined SWOT aspects for grey, blue, and green hydrogen. Methodological application of AHP can be implemented with the following three steps;

Combine the pairwise comparison matrix

A pairwise comparison matrix is a square matrix that represents relative importance or preference between two criteria or alternatives. The construction of the matrix is based on the pairwise comparisons made by the decision-makers to ascertain the relative importance of the criteria and alternatives in comparison to each other. In the majority of cases, the values contained in a matrix reflect the judgments of decision-makers on a numerical scale. This scale is usually based on Saaty's (1980) scale of integers, ranging from 1 to 9. The value 1 is typically assigned when there is equal importance or preference, while values above 1 indicate increasing levels of importance or preference. The pairwise comparison matrix is a fundamental element in deriving the relative weights of criteria employed in the AHP and serves as a foundation for informed decision-making. The comparison matrix A is formed as follows;

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1/n} \\ a_{21} & 1 & \cdots & a_{2/n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad \text{(Eq.1)}$$

i. *Calculate the weights*

Priority weights of each criterion $w_1, w_2, w_3, ..., w_n$ is computed by Eq. 2. where n is the number of criteria.

$$w_i = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad \text{(Eq.2)}$$

ii. *Calculate the consistency ratio (CR)*

Once computing the CR, consistency index (CI) is to be calculated by using Eq. 3.

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad \text{(Eq.3)}$$

Where $\lambda_{\max}$ is the maximum eigenvalue of the matrix which is obtained by using Eq. 4.

$$\sum_{j=1}^{n} a_{ij} w_j = \lambda_{\max} w_i \quad \text{(Eq.4)}$$

Saaty (1980) provided a consistency calculation formula for controlling the consistency of the experts' answers/decision matrix. If $CR < 0.1$ it is considered as consistent.

$$CR = \frac{CI}{RI} \quad \text{(Eq.5)}$$

where RI is the random index and defined as a standard table given in Table 2.

Table 2. Random index

n	1	2	3	4	5	6	7	8
RI	0,00	0,00	0,58	0,90	1,12	1,24	1,32	1,41

Discussion

Within the scope of the study, two consecutive pairwise comparison processes were conducted during the AHP analysis. In the first, pairwise comparison of the main criteria of each hydrogen production method, namely S-W-O-T, was carried out. Subsequently, pairwise comparisons among the sub-criteria under these main criteria were performed, and in the final stage, the values of the sub-criteria, obtained in such a way that their sum is 1 under each main criterion, were multiplied by the weight of the respective main criterion to determine the overall final priority values. For instance, for grey hydrogen, following the second pairwise comparison, the totals of the four strengths under the 'S' criterion were calculated with their weights summing up to 1. Subsequently, these were multiplied by the weight of 'S' (0,278) to compute the priority values globally. Accordingly, the weights for grey, blue, and green hydrogen systems are presented in Table 3 and Figure 3-5 respectively.

Equivalent internal weighting ratios have been established for grey, blue, and green hydrogen types in terms of SWOT analysis. However, transitioning from Grey to Blue hydrogen has resulted in a slight decrease in strengths and opportunities, while weaknesses and threats have increased at similar rates.

Conversely, transitioning from Blue to Green hydrogen has led to a slight increase in opportunities and weaknesses, while strengths have decreased alongside weaknesses and threats.

Following the conducted analyses, opportunities hold the highest weight among the three hydrogen types, followed by strengths, threats, and weaknesses. In terms of their internal ranking, for grey hydrogen, opportunities are prioritized first with a weight of 44.5%, followed by strengths, threats, and weaknesses at 27.8%, 17.6%, and 10.1%, respectively. The 44.5% ratio constitutes the third, first, and second opportunities, respectively. The predominant factor behind these findings is the current preference for grey hydrogen in the short term, which is deemed 2.5 times more significant than cleaner alternatives, while the opportunity to invest in carbon capture technology lags behind. Experts consider the transition to blue hydrogen through carbon capture technology as the weakest opportunity. In terms of strengths, the emergence of the first and third parameters, nearly equal at 2 and 4, respectively, is notable.

Table 3. Priorities of criteria and sub-criteria

SWOT	Grey Hydrogen		Blue Hydrogen		Green Hydrogen	
	Factor Priority	Overall Priority	Factor Priority	Overall Priority	Factor Priority	Overall Priority
Strengths	**0,278**		**0,271**		**0,265**	
S1	0,301	0,084	0,217	0,059	0,406	0,108
S2	0,209	0,058	0,122	0,033	0,177	0,047
S3	0,278	0,077	0,227	0,062	0,217	0,058
S4	0,212	0,059	0,434	0,118	0,200	0,053
Weaknesses	**0,101**		**0,110**		**0,120**	
W1	0,149	0,015	0,317	0,035	0,213	0,026
W2	0,219	0,022	0,206	0,023	0,275	0,033
W3	0,330	0,033	0,252	0,028	0,325	0,039
W4	0,302	0,031	0,225	0,025	0,187	0,022
Opportunities	**0,445**		**0,433**		**0,438**	
O1	0,243	0,108	0,460	0,199	0,298	0,130
O2	0,189	0,084	0,257	0,111	0,267	0,117
O3	0,568	0,253	0,283	0,123	0,436	0,191
Threats	**0,176**		**0,186**		**0,176**	
T1	0,510	0,090	0,317	0,059	0,430	0,076
T2	0,167	0,029	0,280	0,052	0,202	0,036
T3	0,323	0,057	0,402	0,075	0,430	0,076

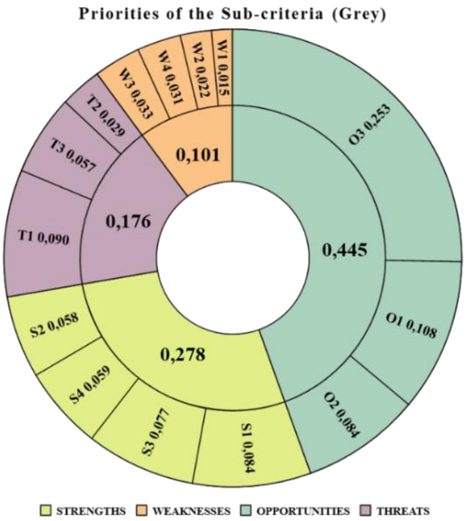

Fig. 3. Priorities of sub-criteria for Grey

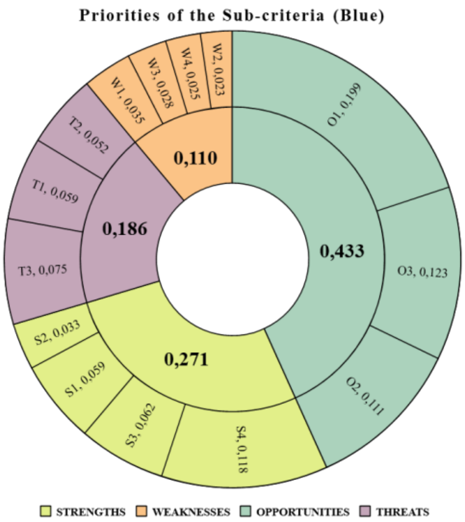

Fig. 4. Priorities of sub-criteria for Blue

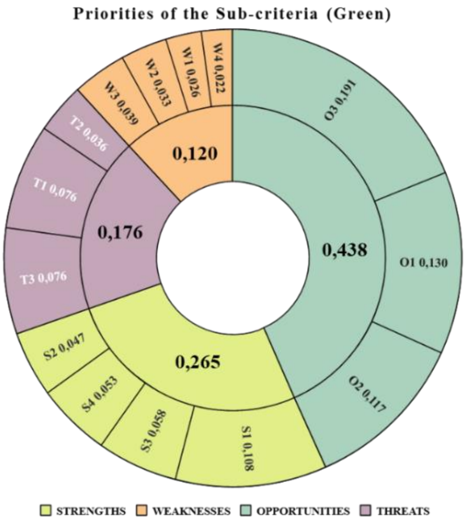

Fig. 5. Priorities of sub-criteria for Green

Overall, with a weight of 27.8%, the strengths of grey hydrogen production, including its more established infrastructure, reliability, and greater emphasis on price advantages compared to other production methods, are considered more crucial compared to blue and green hydrogen. Threats rank third overall, progressing internally in the order of first, third, and second. The ongoing environmental concerns regarding grey hydrogen constitute the most significant threat, followed by potential challenges in regulatory compliance and competition in market share due to the transition to cleaner fuels in the coming years. In the internal ranking of Grey Hydrogen's SWOT analysis, weaknesses are ranked last. Weighted by experts as 3, 4, 2, and 1, the most significant weakness is identified as its limited sustainability in terms of emissions. The generation of carbon emissions from grey hydrogen use is considered the primary weakness, alongside emissions from production to utilization, regulatory challenges, and ongoing environmental concerns.

When analysing the SWOT results for Blue Hydrogen, opportunities are ranked internally as 1, 3, 2. Regulatory support and the advancement of carbon capture technology emerge as the most significant opportunities, while partnership in technological advancements and inter-company knowledge sharing constitute the weakest aspect of opportunities. Regarding strengths, experts have ranked them as 4, 3, 1, 2. The presence of different fuel alternatives in Blue Project production, followed by Blue Hydrogen being a significant milestone in transitioning to zero-carbon fuel, integration with carbon capture systems for emission reduction, and the potential advancements in carbon capture technology, emerge as the strongest aspects of strengths. Examining threats, the presence of technological and operational challenges regarding carbon capture technology on board ships has received the highest threat score. Competition from alternative fuels and uncertainties in emission regulations constitute external threats. In the SWOT ranking, the weaknesses that come last are, in order, 1, 2, 3, and 4, with 1 having the highest impact factor among them. In grey Hydrogen, a limitation in application dependent on CCS (Carbon Capture and Storage) emerges as the most significant weakness. The opportunities for green hydrogen, the strongest fuel option with zero carbon emissions and zero GHG emission, have been analysed in three tiers. Collaboration between ports and ships emerges as the most important opportunity for the technological feasibility of green hydrogen on ships. Following that, project incentives related to the production of green hydrogen from renewable energy sources and the development of electrolysis technology constitute the opportunity items for green hydrogen. The following almost-zero emission, naturally, becomes the strongest parameter, with the following items ranked almost equally. There is no alternative as strong as green hydrogen in terms of zero emission from production to utilization, making zero emission the most important strength, as perceived by experts. In terms of threats, infrastructure limitations and global bunkering challenges for renewable hydrogen emerge as the most important threats, with competition from alternative propulsion systems being evaluated as the last threat. The weaknesses that come last in the SWOT analysis start with relatively low production capacity and high cost, followed by the high-cost infrastructure requirement and dependency on renewable energy on the port side, respectively.

Conclusion

The SWOT analysis conducted in this study provides valuable insights into the strengths, weaknesses, opportunities, and threats associated with grey, blue, and green hydrogen production methods. The findings underscore the dynamic nature of hydrogen production transitions and highlight key factors influencing each method’s viability.

Transitioning between hydrogen types reveals nuanced shifts in their strategic landscapes. While grey hydrogen presents short-term advantages, blue and green hydrogen offer promising opportunities for long-term sustainability and technological advancement. Opportunities, particularly regulatory support and technological advancements, emerge as critical factors driving the transition towards cleaner hydrogen production methods. However, challenges such as regulatory compliance and infrastructure limitations pose significant threats to implementation.

In conclusion, the proposed approach highlights the multifaceted considerations in the transition to sustainable hydrogen production and emphasizes the need for strategic planning and technological advances to overcome challenges and capitalize on opportunities in the evolving energy landscape for a more sustainable and resilient energy future.

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