The Colour-coded Hydrogen Production: An Overview of Environmental Impacts, Economic Implications, Technology Readiness Level and Maritime Skills

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ABSTRACT

Decarbonisation is central to addressing hard-to-abate industries, with the hydrogen economy emerging as a main solution. Currently, hydrogen production predominantly comes from a fossil fuel base, using steam methane reforming (SMR), coal gasification and natural gas responding to the conventional colours of hydrogen (grey, black and brown hydrogen), each with a significant environmental footprint. The growing interest in hydrogen production has led to further research into existing and alternative hydrogen production methods, giving rise to a spectrum of hydrogen colours. Darker colours are typically associated with fossil fuels, whereas lighter colours, particularly green derived from renewable energy sources, are considered cleaner alternatives. Additionally, hydrogen production processes include methane pyrolysis and thermolysis/thermochemical, highlighting the importance of distinguishing between the different colours of hydrogen. The study provides an overview of the 10 hydrogen colours, detailing their production process, sources of energy and the four environmental impacts focusing on eutrophication, global warming potential (GWP), acidification and resource depletion. Furthermore, the study examines the technology readiness levels (TRLs) and the cost of hydrogen production in South Africa. The results indicate that sustainable hydrogen production methods, such as green hydrogen, cost more than the conventional alternatives. Conventional hydrogen colours have reached full technology maturity (TRL 9), whereas the newer technologies remain in their infancy. Additionally, conventional hydrogen production methods exhibit higher environmental impacts compared to more sustainable hydrogen alternatives. In addition, the study highlights the need for further skills development to support the integration of alternative fuels, particularly the various colours of hydrogen, within maritime sector applications.

Keywords: colours of hydrogen, CCUS, blue, green, yellow, black, brown, grey, orange, pink, red, turquoise, environmental impact, costs, technology readiness level, maritime skills

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I INTRODUCTION

In recent years, the hydrogen economy has gained momentum, predominantly in the hard-to-abate industries such as transportation, cement, agriculture and steel, as part of decarbonisation efforts. As global energy demand rises by 4.6 per cent per annum, the average temperature continues to increase (Ahmad & Zhang, 2020). According to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021), without further interventions to curb the temperature rise of 1.5 °C above pre-industrial levels, as stipulated in the 2015 Paris Agreement, climate-related disasters will persist. To mitigate climate change, new hydrogen production technologies have been introduced, including carbon capture, utilisation, and storage (CCUS) with cryogenic air storage. An investment of USD750 billion has been allocated to facilitate the green energy transition (Ghosh & Chhabra, 2021; Sikiru et al., 2024); however, this has been deemed insufficient to fully achieve decarbonisation (International Renewable Energy Agency [IRENA], 2021).

The production of low-carbon hydrogen is recognised as a viable decarbonisation strategy, mainly applicable in countries with abundant natural resources such as South Africa. Investment in hydrogen production has surged, particularly following the Covid-19 pandemic, as evidenced by an increase in hydrogen electrolyser capacity. The transition to renewable energy has led to a 30 per cent rise in global renewable energy generation (Warner & Jones, 2017; Meckling & Hughes, 2018). However, this transition presents challenges, particularly regarding the energy storage technologies required to stabilise the energy supply. In addressing these challenges, technologies such as batteries, cryogenic air energy storage and CCUS must be maximised, with green hydrogen explored as a potential energy carrier (Bajpai et al., 2022).

Hydrogen has been used for centuries, dating back to the 19th century, across various industries for multiple applications (Winter, 2009). Over time, advancements in hydrogen production methods have led to the adoption of hydrogen colour classifications. These classifications are associated with production methods, energy sources and environmental impacts. The colour-coded system is essential for differentiating between fossil fuel-based, renewable and nuclear-derived hydrogen. South Africa presents significant potential for hydrogen production across these categories.

As an energy carrier, hydrogen can be produced by various methods, depending on regional climatic conditions and resource availability. Initially, hydrogen was primarily derived from fossil fuels. However, as industries strive for decarbonisation, new production methods and hydrogen colours have emerged. Despite this diversification, fossil fuel-based hydrogen production remains dominant because of its affordability and accessibility. Over the past five years, significant support has emerged for reducing fossil fuel dependence, positioning hydrogen as a potential commodity (International Energy Agency [IEA], 2022). Nevertheless, despite increased investment in hydrogen economies, adoption has been slow. Of the 94 million tonnes of hydrogen produced globally, only 0.004 per cent is green hydrogen, while fossil fuel-based hydrogen (predominantly black hydrogen) accounts for 80 per cent of total production (EIA, 2022), primarily using steam methane reforming (SMR), which generates grey hydrogen.

Hydrogen colours, such as brown, grey, green and black, have been widely accepted by experts, policymakers, industries and scholars to distinguish between different hydrogen production processes. Grey, black and brown hydrogen are associated with high carbon emissions, whereas green hydrogen is recognised as a cleaner alternative. In response to emissions concerns, CCUS technology has been introduced to reduce carbon dioxide (CO_2) emissions, resulting in blue hydrogen. According to IRENA (2022), blue hydrogen is produced using fossil fuel-based methods but incorporates CCUS technologies to mitigate the environmental impacts. The overarching goal of hydrogen colour classification is to differentiate hydrogen sources, assess environmental impacts and evaluate CO_2 emission levels to support decarbonisation.

Various hydrogen production methods have been explored, including thermochemical and thermolysis processes, electrolysis and gasification, SMR, biological processes, pyrolysis and biochemical methods.

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Additionally, nuclear and renewable energy sources are gaining traction as cleaner alternatives. However, in South Africa, societal acceptance and regulatory barriers have hindered nuclear energy adoption beyond its current medical applications (Makhubela, 2024), limiting pink and red hydrogen production.

Furthermore, while skills related to hydrogen production already exist, particularly in the grey, brown and black hydrogen sectors, they are not explicitly developed in the maritime industry. The 2023 Greenhouse Gas (GHG) Strategy document, which forms part of the International Maritime Organization's (IMO) comprehensive approach to decarbonisation, prioritises the use of alternative fuels such as ammonia, methanol and green hydrogen to achieve emissions reductions (Bilgili & Ölçer, 2024; Joung et al., 2020). However, the IMO's current focus on a limited selection of hydrogen types overlooks the potential benefits of considering the full spectrum of hydrogen production methods. Incorporating other hydrogen colours into maritime decarbonisation strategies would enable the industry to assess their feasibility, availability and regional suitability more comprehensively.

To facilitate this transition, skills development initiatives must be integrated into maritime education and training (MET) programmes. This is essential to ensure that the workforce can adapt to emerging technologies and alternative fuel applications in the maritime industry. Specifically, upskilling and reskilling efforts should be prioritised for individuals with existing qualifications, while new educational pathways should be developed to equip professionals with expertise in operating vessels powered by alternative fuels and managing retrofitting processes.

This study critically examines the costs of hydrogen production, TRLs, environmental impacts and the maritime skills required for hydrogen integration. A desktop analysis was conducted to achieve the study objectives, providing an in-depth assessment of the sector's preparedness for a multi-faceted hydrogen economy.

II OVERVIEW OF COLOUR-CODED HYDROGEN

Hydrogen colours classification lacks standardisation, leading to inconsistencies in terminology in the literature. As green, grey and blue hydrogen are consistently defined (Navas-Anguita et al., 2021), while other classifications, such as orange (Panić, Cuculić & Ćelić, 2022) and turquoise (Schneider et al., 2022), vary across sources. Nuclear-derived hydrogen colours remain debated, with some studies categorising nuclear hydrogen as red (El-Emam, Ozcan & Zamfirescu, 2020) or pink (Fernández-Arias et al., 2024). This study classifies nuclear-powered electrolysis as pink hydrogen, while red hydrogen is associated with electrolysis and the thermochemical/thermolysis process. Other colours such as white, gold and purple were not included in the study. Additionally, yellow and orange hydrogen classifications vary, with yellow hydrogen typically associated with solar-powered electrolysis and orange hydrogen linked to grid power-electrolysis (Panić, Cuculić & Ćelić, 2022; Germscheidt et al., 2021). See Table 1 for the colours of hydrogen, source of energy and production process.

In South Africa, black, brown and grey hydrogen remain the most commonly used hydrogen. Black hydrogen, derived from bituminous coal by gasification, is cost-effective and has high syngas production. Producing black hydrogen and grey requires 1 kg of coal to generate 0.1 kg of hydrogen (Garcia, 2024). The gasification process converts coal into syngas, a mixture primarily composed of carbon monoxide and hydrogen. This method also applies to brown hydrogen, which is produced using lignite coal or biomass by means of gasification. Black hydrogen production is well established and widely used in industries such as agriculture and chemicals for ammonia synthesis. South Africa, with its abundant coal reserves of coal, uses black hydrogen for commercial production. Along with 15 coal-fired power plants, South Africa ranks as the world's seventh-largest coal producer (Gule, 2021). However, the country's heavy reliance on coal is a major contributor to high carbon emissions.

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The coal gasification process involves reacting coal with steam and air or oxygen in a controlled environment to produce syngas, which contains hydrogen, carbon monoxide and various pollutants, such as sulphur and methane (Aziz, Darmawan & Juangsa, 2021). The same process applies to brown hydrogen production, although lignite coal is used instead of bituminous coal. Biomass gasification produces brown wood and agricultural residues. Biomass gasification occurs at temperatures between 900 °C and 2 000 °C, with optimal biomass moisture content ranging from 9 to 22 per cent to ensure high-quality syngas production (Khlifi, Pozzobon & Lajili, 2024). Biomass gasification (brown) offers several advantages, including affordability, ease of transportation and minimal distribution losses (Aziz, Darmawan & Juangsa, 2021). As a result, biomass has the potential to play an important role in the future hydrogen energy system.

Red hydrogen is a nuclear-derived energy source produced using thermolysis and thermochemical water splitting. Thermolysis involves the thermal decomposition of water in a single-step reaction. This process requires a substantial amount of heat to break down water molecules, with operating temperatures ranging from 1 700 °C to 4 000 °C (Pinsky et al., 2020). However, to fully exploit its potential, temperatures exceeding 4 000 °C are desirable. Such heat levels can be achieved by using biomass, solar thermal and geothermal energy sources. A key challenge associated with solar thermal energy is its dependence on a continuous heat supply to sustain operations. Solar energy is intermittent, relying on sunlight availability. However, regions with abundant solar resources, such as the Northern Cape in South Africa, could serve as exceptions (Sebele, 2024). Another obstacle is the regulatory and operational challenges related to nuclear energy in South Africa, which may hinder the feasibility of thermolysis-based hydrogen production (Makhubela, 2024).

One major drawback of thermolysis is the extreme operating temperatures required, which present significant occupational health and safety risks. Suitable protective gear and infrastructure are essential to withstand such harsh conditions. Another critical challenge is the separation of hydrogen and oxygen as both gases are released from a single outlet, increasing the risk of recombination, which could lead to hazardous, explosive reactions (Pinsky et al., 2020). One potential solution is quenching, which inhibits hydrogen and oxygen recombination. However, quenching is only effective at temperatures between 1 500 °C and 2 000 °C, significantly lower than the 4 000 °C required for efficient thermolysis (Murmura & Vilardi, 2021). Despite these challenges, thermolysis holds considerable potential for red hydrogen production on a small scale, provided that safety and efficiency concerns are adequately addressed.

Thermochemical water splitting is another method of red hydrogen production. In contrast to thermolysis, this process involves a net reaction of water dissociation alongside a series of intermediate chemical reactions. A significant advantage of thermochemical water splitting is that it does not require catalysts for single chemical reactions (Li et al., 2022; Li et al., 2020; Murmura & Vilardi, 2021). Additionally, water serves as the primary reactant and all chemicals used in the process are recycled within the thermochemical cycle. Further advantages of this method include the elimination of the need for hydrogen separation, high efficiency, minimal to no electrical energy consumption and moderate temperature requirements compared to thermolysis (Li et al., 2020). These factors make thermochemical water splitting a promising approach to red hydrogen production, offering both sustainability and operational feasibility (Li et al., 2022).

The production of orange hydrogen primarily relies on electrolysis using electricity from the energy grid (Panić, Cuculić & Ćelić, 2022; Germscheidt et al., 2021). The emissions associated with this form of hydrogen production depend entirely on the energy sources used in its production, which can vary significantly between regions. In a country such as South Africa, where the energy grid is powered entirely by coal, orange hydrogen production results in high CO_2 emissions (Germscheidt et al., 2021). In contrast, Canada benefits from a cleaner energy mix, consisting of approximately 30 per cent geothermal and 70 per cent hydropower, leading to significantly lower emissions (Agu, Tabil & Mupondwa, 2023).

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Turquoise hydrogen is produced by decomposing hydrocarbons via methane pyrolysis at high temperatures, resulting in the separation of methane into gaseous hydrogen and solid carbon (Schneider et al., 2020). In contrast to other hydrogen production methods, turquoise hydrogen does not generate CO_2 or oxygen as by-products, eliminating the need for secondary processing. This reduction in additional processes translates to lower capital costs and operational expenditure (OPEX). A key advantage of this method is the high concentration of hydrogen in the gas stream, which minimises the need for extensive downstream purification. The cost of methane pyrolysis is primarily influenced by the price of the feedstock (natural gas), the specific processing route employed and the use of the solid carbon by-product (Schneider et al., 2020). There are several pyrolysis techniques for producing turquoise hydrogen, including high-temperature thermal black, molten metal, solid catalytic and plasma reforming. These processes are further explored in the publication by Dagle et al. (2017). The heat required for methane pyrolysis can be supplied by concentrated solar energy, hydrocarbon combustion or electricity. To accelerate the production process, both carbon- and metal-based catalysts are employed.

Green hydrogen, often referred to as clean hydrogen, is produced using renewable energy sources for electricity to power water electrolysis. These renewable sources include hydropower, solar, biomass, geothermal and wind energy. Green hydrogen is characterised by minimal to no carbon emissions, hence its classification as clean hydrogen. However, life-cycle assessments conducted on the entire value chain of green hydrogen indicate that emissions do exist, albeit significantly lower than those associated with other hydrogen colours (Hren et al., 2023). This highlights the potential for storing surplus renewable energy in the form of hydrogen as a viable solution to future energy needs. Because its production method via water electrolysis, green hydrogen achieves a purity level of 99 per cent, making it suitable for various industries and even for export (Ajanovic, Sayer & Haas, 2022). The production process involves splitting water molecules into hydrogen and oxygen using electricity generated from renewable energy. Key components in this process include cathode and anode electrodes, a power source, and an electrolyte.

The efficiency of electrolysis technologies varies, with the most common methods being solid oxide electrolysis (SOE), alkaline electrolysis and proton exchange membrane (PEM) electrolysis. Electrolysis is critical for green hydrogen production, particularly in hard-to-abate industries such as transportation, where reducing emissions is essential. Alkaline electrolysis, with an efficiency of 56 to 70 per cent (Sundén, 2019), is a mature and cost-effective technology compared to other electrolysers. However, its drawbacks include slow dynamic response, gas permeation and corrosive impacts. Despite these challenges, improvements in reliability and durability have been made over the years. PEM electrolysis, one of the most widely used technologies in South Africa, offers an efficiency of 60 to 80 per cent, a rapid start-up time (Guo, Zhou & Liu, 2019), fast response rates and a compact design. It also produces highly pure hydrogen. However, PEM electrolysers are expensive and require noble metals because of their acidic medium, posing a significant cost barrier (Wang, Cao & Jiao, 2022). Efforts to reduce reliance on noble metals remain an ongoing challenge. SOE electrolysis is more efficient than the aforementioned technologies (Sundén, 2019), with lower operating costs and energy requirements. It also benefits from high thermodynamic efficiency (650–850 °C) and fast reaction kinetics (Wolf et al., 2023). However, its main drawbacks include passivation and electrode degradation (Sundén, 2019).

In South Africa, green hydrogen production remains in its early stages, primarily due to regulatory constraints and the need for comprehensive feasibility studies. Nonetheless, solar farms have been installed across the country, along with onshore wind turbines, and future offshore wind projects are planned for Richards Bay. One of the significant challenges of green hydrogen production is its high water demand, which is particularly concerning in a water-scarce country such as South Africa. The country has experienced severe droughts in recent years, with instances of 'Day Zero' or complete water shortages (Ramantswana et al., 2021). Producing 1 kg of hydrogen requires approximately 9 kg of water, making large-scale production difficult in a country with limited water resources (Kumar et al., 2024). Desalination could be a potential solution to address this issue. However, it must be implemented

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carefully to prevent excessive salinity in South African coastal waters. An alternative approach could involve repurposing extracted salt for commercial use in the salt industry, creating additional economic benefits.

Blue hydrogen is an attractive option due to its relatively low carbon emissions. This form of hydrogen is produced from fossil fuels but is combined with CCUS technology to mitigate its environmental impact (Incer-Valverde et al., 2023). Compared to green hydrogen, blue hydrogen is generally more cost-effective, making it a financially viable alternative. Blue hydrogen is considered carbon neutral, contrasting other affordable hydrogen variants such as black, brown and grey hydrogen, which have significantly higher emissions. Because it enables continued fossil fuel use while incorporating carbon capture methods, blue hydrogen helps reduce CO_2 emissions and lowers the carbon footprint of major fossil fuel-producing nations, including the United States, China, South Africa, Russia, Iran and Norway. The captured CO_2 can be repurposed for industrial applications or stored underground in geological formations. The production of blue hydrogen typically involves a combination of SMR and CCUS technologies (Baquero & Monsalve, 2024). This approach significantly reduces the amount of CO_2 released into the atmosphere, increasing carbon capture efficiency while producing high-purity hydrogen. SMR, which relies on fossil fuels to generate hydrogen, naturally results in CO_2 emissions (Massarweh et al., 2023). However, the integration of CCUS ensures that these emissions are captured rather than released, making blue hydrogen a more sustainable alternative.

The production of grey hydrogen primarily involves SMR, one of the most mature and widely used methods for hydrogen production. Grey hydrogen was first implemented in the United States in the 1930s, a period marked by abundant methane availability (Ajanovic, Sayer & Haas, 2022). However, by the 1960s, there was a transition to using syngas as a feedstock. Despite its widespread use, grey hydrogen production is both energy- and carbon-intensive as it generates carbon monoxide and hydrogen in the form of syngas as a result of the reaction of water with methane (light hydrocarbons). According to Ji and Wang (2021), grey hydrogen accounts for 96 per cent of global hydrogen production. The sources of grey hydrogen production globally are distributed as follows: natural gas (49 per cent); coal (18 per cent); and methane (hydrocarbons) (29 per cent). This highlights the fact that a significant proportion of global hydrogen production originates from SMR. However, the SMR process releases large quantities of CO_2 into the atmosphere, contributing to climate change.

SMR relies on a nickel-based catalyst at approximately 800 °C to facilitate the reaction. The process involves several key stages:

- **Reforming reaction**: Water vapour reacts with methane to produce syngas (a mixture of carbon monoxide and hydrogen).
- **Water–gas shift (WGS) reaction**: Carbon monoxide is converted into CO_2 and hydrogen by reacting with steam, increasing hydrogen yield.
- **CO_2 removal**: CO_2 is separated to enhance hydrogen purity, typically using a CO_2-absorbing device (Garcia, 2015).

Although grey hydrogen production is well established, certain challenges remain, particularly in optimising reaction temperatures and increasing natural gas conversion efficiency. Lowering the temperature of the SMR process can enhance energy efficiency by reducing the energy required for preheating and enabling faster start-up times, without the need for a separate carbon monoxide reactor (Navas-Anguita et al., 2021). The implementation of lower-temperature SMR could also help reduce OPEX and construction costs (Angeli et al., 2014).

Black hydrogen is a well-established hydrogen production technology derived from bituminous coal using a process known as gasification. This form of hydrogen has been widely used in various industries, including agriculture and chemicals, particularly for ammonia production (Dawood, Anda & Shafiullah, 2020). In regions such as South Africa, where coal resources are abundant, black hydrogen is commonly used for ammonia production (Baquero & Monsalve, 2023). South Africa has long relied on black hydrogen

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for commercial production, operating 15 coal-fired power plants nationwide, making it the seventh-largest coal producer in the world. However, the country's heavy dependence on coal has been linked to high carbon emissions.

When produced using biomass gasification, brown hydrogen is considered one of the most accessible and cost-effective hydrogen production methods. In this process, chemical agents convert biomass into a gaseous mixture, also generating syngas. Similar to coal gasification, biomass gasification operates at high temperatures ranging from 900 °C to 2 000 °C (Baquero & Monslave, 2024). Maintaining biomass moisture content between 9 and 22 per cent is essential to ensure quality output. Biomass gasification is highly efficient because of the high calorific value of its products, including hydrogen, carbon monoxide and methane. The types of biomass that can be used for brown hydrogen production include solid organic waste from residential areas (often sourced from municipal landfill sites), wood and agricultural waste (Schneider et al., 2024). Because of its affordability, ease of transportation and minimal distribution losses, biomass has the potential to play a significant role in the future hydrogen energy system.

Table 1: Hydrogen colours and their source of energy and production process

Hydrogen colour	Source of energy	Production process
Grey	SMR	Natural gas
Blue	Coal gasification/natural gas with carbon capture	Natural gas and coal
	SMR with carbon capture	Natural gas
Green	Electrolysis via wind energy	Water
Red	Thermolysis/thermochemical nuclear water splitting	Water
Turquoise	Pyrolysis	Natural gas
Yellow	Electrolysis using solar energy	Water
Pink	High-temperature electrolysis powered by nuclear energy	Water
Black	Bituminous coal	Gasification
Brown	Lignite coal	Gasification
Orange	Mix grid electricity (conventional power grid electricity)	Water

III LIMITATIONS

This study was limited to an analysis of 10 colours of hydrogen, excluding purple hydrogen, which was not considered in the scope of the research. Furthermore, the study does not investigate the extensive details regarding the various hydrogen production methods for each colour. Another limitation is that the research is based solely on a desktop analysis, relying exclusively on published literature from reputable sources and institutions. As a result, the study does not incorporate primary data or experimental findings.

IV METHODOLOGY

The method that was used for this study was a desktop analysis to try and identify the different colours of hydrogen, even though some scholars included different colours such as purple, gold and white hydrogen, which, in this article, were not used. The selection of colours was as follows: black, grey, brown, blue, green, turquoise, pink, red, orange and yellow hydrogen, each colour symbolising the emissions, with black being the worst and green being clean. In this study, the

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search engines used were Science Direct, Scopus and Google Scholar to retrieve peer-reviewed articles and published reports. Certain terms were used to search the literature, namely the 'environmental impact of hydrogen', 'codes of hydrogen', 'hydrogen rainbow', 'hydrogen technology readiness', 'hydrogen South Africa', 'hydrogen production methods', 'hydrogen skills development', 'hydrogen maritime education and training', and 'maritime skills and decarbonisation'. A total of 159 papers were identified, however, I ended up with 66 papers after applying the exclusion criteria, only selecting published reports and peer-reviewed articles.

V ENVIRONMENTAL IMPACTS

The classification of hydrogen colours varies between scholars; however, each type of hydrogen is characterised by its associated environmental impact during production. The emissions generated by each hydrogen colour depend on both the source of energy used and the hydrogen feedstock. Hydrogen produced by means of water electrolysis generally has lower emissions compared to hydrogen derived from fossil fuels, which typically results in higher CO_2 emissions (Cho, Strezov & Evans, 2023). However, blue hydrogen is an exception as it incorporates CCUS to significantly reduce or eliminate CO_2 emissions (Sadeghi & Ghandeharium, 2023).

Nevertheless, emissions can vary depending on the system boundary and inventory used in assessments. Some studies consider the entire life cycle, while others may include or exclude transportation emissions (Lubis, Dincer & Rosen, 2008). Additionally, although green hydrogen is often viewed as the most environmentally friendly option, it requires a substantial amount of water, which poses challenges in water-scarce regions such as South Africa. In such cases, desalination could be a viable solution but careful management of brine discharge is critical to avoid negative environmental impacts (Linden, 2024; Mavukkandy et al., 2019).

A comparative analysis of the environmental impacts of the production different hydrogen colours was conducted, focusing on acidification (this form of environmental impact focuses on effects of capacity of acid substance on water, soil, and vegetation) (Sadeghi & Ghandeharium, 2023; Cho, Strezov & Evans, 2023), eutrophication (freshwater) looks into measuring the nutrient enrichment and how it impacts aquatic ecosystem (Cho, Strezov & Evans, 2023), resource depletion (looks into the potential of depletion of renewable and non-renewable resources Sadeghi and Ghandeharium, 2023) and global warming potential (GWP) (the quantification of contribution of substances to the global warming in comparison to CO_2) (Cho, Strezov & Evans, 2023). The study used median values to assess each impact (see Figure 1). The analysis highlights black hydrogen as having the highest environmental impact, with acidification at 29 kg SO_2 eq. per kg H_2, eutrophication at 0.04 kg PO_4^{-3} eq. per kg H_2 and GWP at 21 kg CO_2 eq. per kg H_2, while resource depletion is relatively low (0.000014 kg Sb eq. per kg H_2) (Mehmood et al., 2025). These values reflect the significant environmental degradation associated with black hydrogen, primarily due to the substantial carbon emissions released into the atmosphere.

Grey hydrogen also exhibits a high environmental impact, particularly in terms of resource depletion (0.37 kg Sb eq. per kg H_2) and GWP (9.4 kg CO_2 eq. per kg H_2) (Mehmood et al., 2025), making it the third highest contributor to GHGs after orange hydrogen. The environmental footprint of orange hydrogen is largely dependent on the energy mix of the electricity grid. In a country such as South Africa, where the electricity grid is predominantly coal-based, orange hydrogen would have a substantial carbon footprint. However, this may not be the case in countries with cleaner energy grids, such as Iceland. Brown hydrogen, which is derived from biomass gasification, has relatively low eutrophication and resource depletion impacts (0.0038 kg PO_4^{-3} eq. per kg H_2) (Mehmood et al., 2025).). Despite being sourced from biomass, its environmental footprint is lower than that of fossil fuel-based hydrogen. Pink hydrogen (produced using nuclear energy) has the lowest overall environmental impact, with zero eutrophication and resource depletion, 1.3 kg CO_2 eq. per kg H_2 for GWP and 3.9 kg SO_2 eq. per kg H_2 for acidification (Mehmood et al., 2025).). However, while emissions are minimal, considerations around nuclear safety, radiation risks, and potential accidents must be considered.

Blue hydrogen produced using a combination of SMR with CCUS or coal gasification with CCUS has an

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environmental impact three times lower than that of black hydrogen and half that of grey hydrogen in terms of GWP. However, blue hydrogen still exhibits a high acidification potential of 13 kg SO_2 eq. per kg H_2 (Mehmood et al., 2025). Additionally, CCUS technology is not yet fully developed and is still being explored in Europe (eg France). Questions remain about the long-term fate of captured carbon and whether it is permanently stored, used in industrial applications such as urea production or potentially re-released into the atmosphere (Sadeghi & Ghandeharium, 2023).

Although green hydrogen is generally regarded as the least environmentally damaging option, it still has a notable acidification impact (3 kg SO_2 eq. per kg H_2) (Mehmood et al., 2025). Yellow hydrogen, produced from solar energy, has environmental impacts primarily associated with land clearance for solar farm construction. Water consumption is another critical factor when assessing environmental impact. Grey hydrogen requires approximately 7 kg of water per kg of hydrogen produced, whereas green hydrogen requires 9 kg of water per kg of hydrogen, which is a significant concern in water-scarce regions. Since CCUS technology is in its early stages of development, turquoise hydrogen, which produces solid carbon instead of CO_2, may present a more sustainable alternative. However, in South Africa, the most viable hydrogen colours to explore include green, yellow, orange, pink and red as they align with the country's existing energy resources and infrastructure.

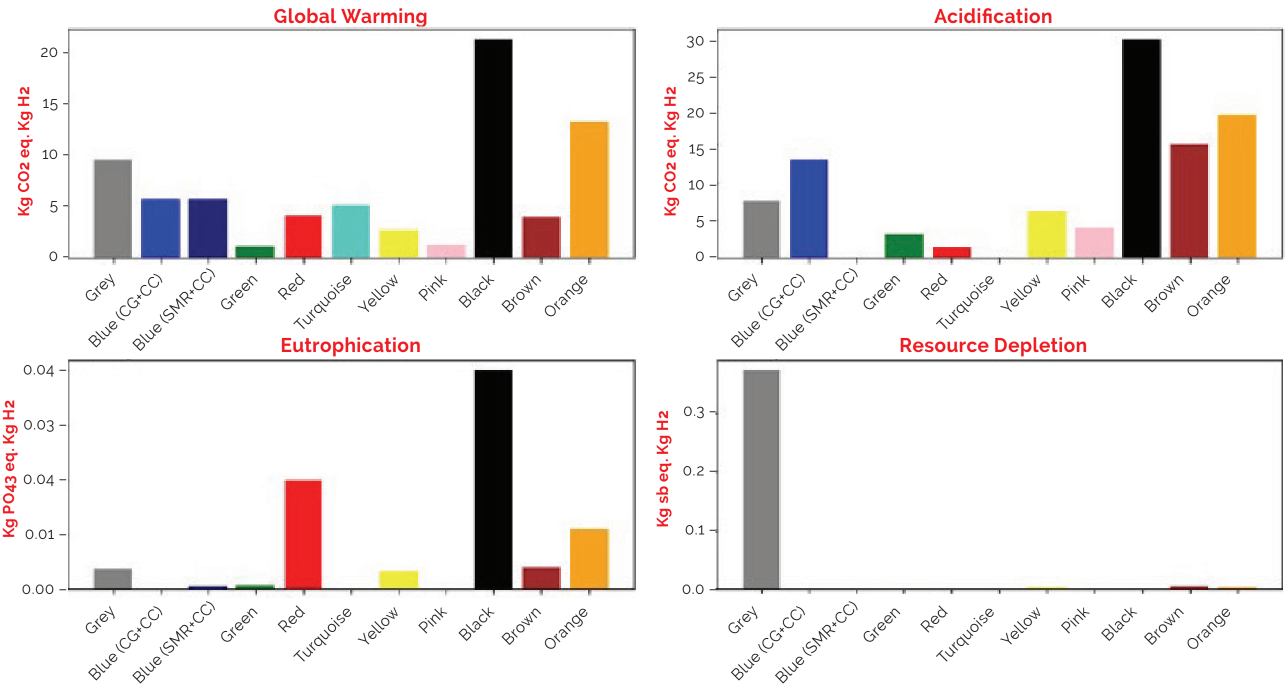

Figure 1: Median value of 10 colours of hydrogen and their environmental impact

VI TECHNOLOGY READINESS LEVEL

The TRL framework provides a structured approach to assessing the maturity of a technology from its conceptual phase to its eventual commercial deployment. The stages of development are illustrated in Figure 2.

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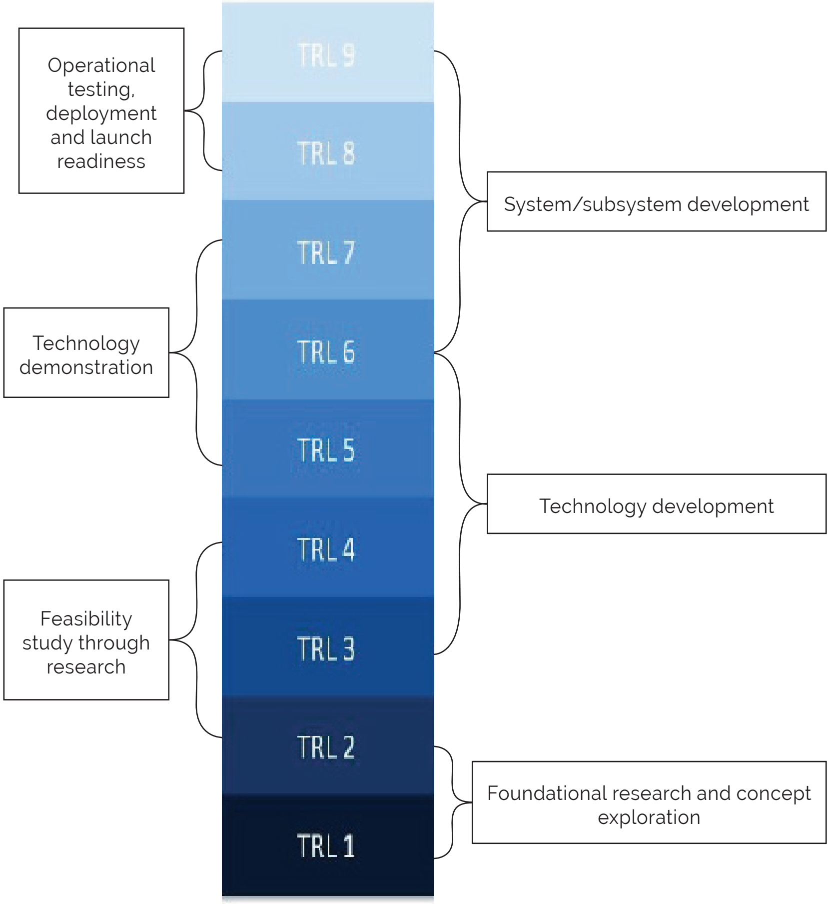

Figure 2: Description of the TRL of hydrogen production technologies

The TRL framework is essential for understanding where a technology stands in its development lifecycle, from basic research through to commercial readiness. This framework helps to identify potential gaps in the technology development process and can guide investment, innovation and policy.

Technology readiness level of hydrogen production technologies

The technology readiness of hydrogen production methods varies significantly depending on the colour of the hydrogen. The conventional methods, namely black, brown and grey hydrogen, are highly mature, with TRL 9 representing fully commercialised technologies (The Royal Society, 2018). These technologies have been in use for decades and are well established in the industry, particularly when using coal gasification, SMR and biomass gasification (Li et al., 2024). On the other hand, blue hydrogen, which combines SMR with CCUS, is still at an early stage of development (Bukar & Asif, 2024). Although it has made significant strides in certain countries, such as France, the United States, and Canada, CCUS is not yet fully commercialised (Khan et al., 2022). It is currently between TRL 1 and TRL 3, as the technology is still being explored, with challenges remaining around scalability, cost and long-term carbon storage. The turquoise hydrogen production process, using pyrolysis, is also in its early stages, with a TRL of 6. This method is still undergoing experimentation and requires further development to make it commercially viable. For yellow and red hydrogen, which are produced using water splitting technologies (such as thermolysis and thermochemical

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processes), the technologies are in the early stages of development at TRL 3. These technologies show promise but are still primarily in the research phase, with much work needed to bring them to market. As for pink, green and orange hydrogen, these methods primarily use electrolysis, a process that splits water into hydrogen and oxygen using electricity. These methods vary in terms of their TRL depending on the type of electrolyser used.

- Alkaline electrolysis is a well-established technology with a TRL of 9, having been commercially available for many years.
- PEM electrolysers have reached TRL 9 and have become more affordable in recent years due to technological advancements.
- SOE, on the other hand, is still in the early stages of development, with TRL of 4–5. Although SOE has the potential to operate efficiently at higher temperatures, it faces challenges in terms of cost and durability at scale.

In South Africa, the TRL of hydrogen production methods reflects global trends but is influenced by regional factors such as resource availability, infrastructure and public perception (Makhubela, 2024; Hammi et al., 2024). Conventional hydrogen production methods (black, grey and brown) are well developed and commercialised, with TRL 9 (See Table 2). Blue hydrogen, incorporating CCUS, is still emerging in South Africa, with TRL between 1 and 3 due to the infancy of the technology. Turquoise hydrogen (pyrolysis), yellow hydrogen (solar electrolysis) and red hydrogen (thermolysis/thermochemical) are also in the early stages of development, with TRL 3. Pink hydrogen is limited because of the nuclear infrastructure available in South Africa and public perception remains a challenge. Orange hydrogen, which uses a mixed electricity grid, is still in early development, with a TRL of 4, although the grid's energy mix (largely fossil fuel-based) plays a role in its future viability. Green hydrogen, produced via electrolysis, has a TRL of 5–7 in South Africa (The Royal Society, 2018), reflecting the current stage of development and investment in renewable energy infrastructure. According to the South African Hydrogen Economy Roadmap, green hydrogen has made substantial progress but still faces challenges in scaling up production.

The TRL of hydrogen production technologies varies across the different colours of hydrogen. Conventional methods such as black, grey and brown hydrogen are well established at TRL 9, while emerging technologies such as blue, turquoise, yellow and red hydrogen are still in the early stages, with TRLs ranging from 1 to 6. In South Africa, conventional methods are the most commercially viable, while green hydrogen is gaining momentum, particularly with the growth of renewable energy resources. The advancement of blue hydrogen and CCUS technologies remains an area of focus but challenges in scalability and cost remain. As these technologies evolve, TRLs will continue to provide a useful measure of progress in the development of hydrogen production method.

Table 2: Hydrogen production colours and TRL in South Africa

Colours of Hydrogen	Technology Readiness Level
Black	9
Brown	9
Grey	9
Blue	1–3
Orange	4
Yellow	1–3

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Colours of Hydrogen	Technology Readiness Level
Red	1–3
Pink	2–4
Turquoise	1–3
Green	5–7

VII COSTS OF HYDROGEN

The capital costs associated with each hydrogen colour are primarily influenced by the commercialisation of the production technology and the maturity of the method used. Established methods tend to be more cost-effective due to economies of scale, whereas emerging technologies require significant investment in specialised equipment and infrastructure, leading to higher capital expenditure (CAPEX) and OPEX. The most commercially advanced hydrogen production methods black, grey and brown hydrogen have been in use for decades, making them the most affordable. In contrast, blue hydrogen, which incorporates CCUS, has not been widely explored in many countries, including South Africa, making its costs higher than those of conventional hydrogen production.

Newer hydrogen production methods such as yellow, green, pink and red hydrogen vary in cost. Yellow hydrogen, generated from solar-powered electrolysis, has the highest cost due to the technological complexity and the capital investment required for chemical storage, thermal integration and solar reactors. On the other hand, green, pink and red hydrogen are associated with lower CAPEX and OPEX, particularly in regions with abundant renewable or nuclear energy resources. These cleaner hydrogen options, when affordable, can produce high-purity hydrogen.

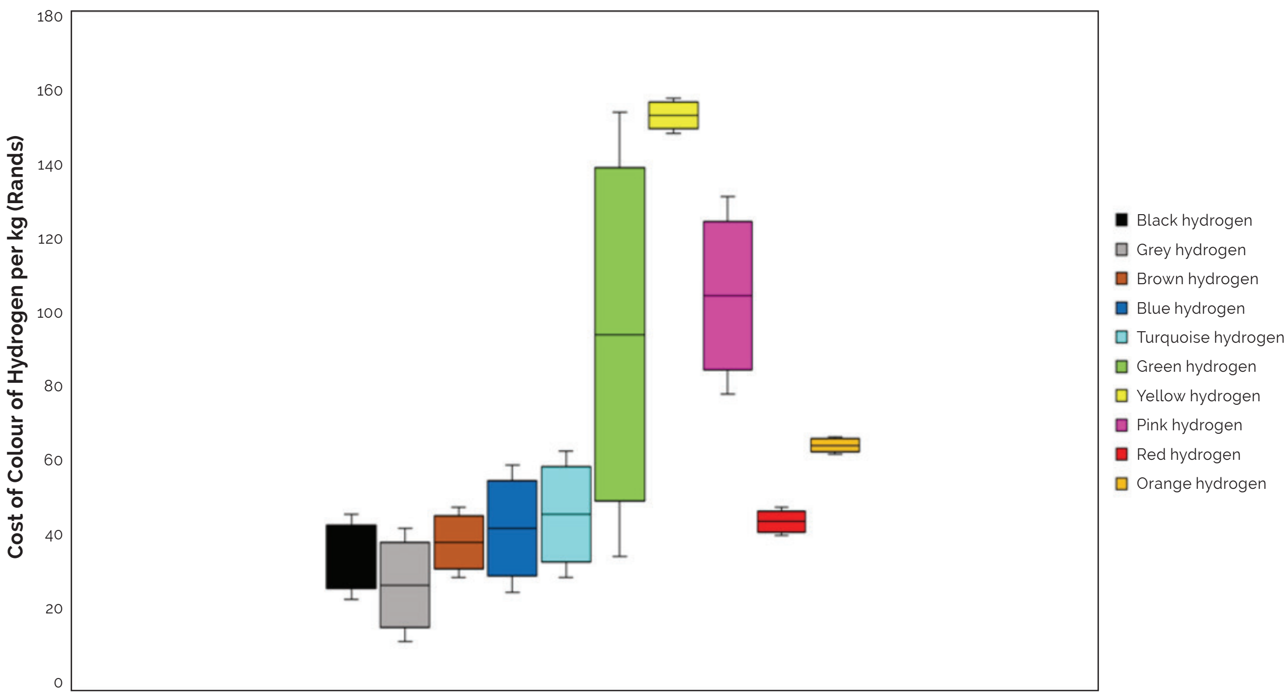

Figure 3: Cost for colours of hydrogen per kg (in rands)

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Cost comparison of hydrogen colours

Hydrogen produced using conventional methods (black, grey and brown hydrogen) is relatively affordable, with prices influenced by the cost of feedstock, primarily fossil fuels. However, the potential implementation of carbon taxes in the future may increase the cost of these hydrogen colours as a result of their high CO_2 emissions. A study by Tembe (2023) on the lifecycle analysis of green hydrogen in Saldanha Bay, South Africa, found that, even with the introduction of a carbon tax, the combined cost of conventional hydrogen (including the tax) remained lower than that of cleaner hydrogen alternatives.

According to a cost comparison graph (Figure 3), grey hydrogen is the most affordable, ranging between R13.11 to R43.08 per kg H_2 (Incer-Valverde et al., 2023; United Nations Economic Commission for Europe [UNECE], 2021; IEA, 2019). Black hydrogen follows, with prices between R24.35 and R46.83 per kg H_2 (IEA, 2022; Incer-Valverde et al., 2023). The introduction of carbon taxes could increase the costs of both black and grey hydrogen, making cleaner alternatives such as green, blue and turquoise hydrogen more competitive. Blue hydrogen, which incorporates CCUS, has a price range between R26.22 and R59.94 per kg H_2 (UNECE, 2021), with costs increasing due to the integration of CCUS technology into conventional hydrogen production. Brown and turquoise hydrogen are slightly more expensive than blue hydrogen. Green hydrogen is highly dependent on the energy source used for electrolysis, with costs ranging from R35.59 to R153.60 per kg H_2 (Incer-Valverde et al., 2023). The price variation is largely influenced by the type of renewable energy used, whether wind (onshore or offshore), hydropower or solar. Regions with abundant renewable energy resources, such as South Africa's Northern Cape, are prone to lower green hydrogen costs compared to countries in the Northern Hemisphere that rely more on imported renewable electricity. Yellow hydrogen, produced via solar-powered electrolysis, has the highest cost at between R147.98 and R157.35 per kg H_2 (Incer-Valverde et al., 2023), largely due to the TRL and the cost of implementing large-scale solar electrolysis systems. Pink hydrogen, produced using nuclear power, has a price range of between R78.67 and R131.12 per kg H_2 (Incer-Valverde et al., 2023). Pink hydrogen is more cost-effective in countries with established nuclear infrastructure, such as Japan, South Africa, the United States, China, France and Canada. These nations may pay slightly less because of the existing nuclear power plants, whereas countries without nuclear infrastructure would incur additional import costs. Orange hydrogen, which is derived from grid electricity, varies in cost depending on the energy mix of the grid. If the electricity source includes a significant portion of fossil fuels, the price of orange hydrogen is lower, ranging from R62.75 to R67.43 per kg H_2 (Incer-Valverde et al., 2023).

Hydrogen costs in South Africa

In South Africa, grey hydrogen remains the cheapest option compared to emerging alternatives such as green hydrogen. According to the South African Hydrogen Valley Report (2021), the projected costs of grey and green hydrogen vary across different hubs:

- Johannesburg

  2025: Green hydrogen – R115.24,
  grey hydrogen – R41.56

  2030: Green hydrogen – R88.79,
  grey hydrogen – R56.68

- Durban/Richards Bay

  2025: Green hydrogen – R103.91

  2030: Green hydrogen – R94.46,
  grey hydrogen – R90.68

- Limpopo/Mogalakwena

  2025: Green hydrogen – R109.57

  2030: Green hydrogen – R92.57,
  grey hydrogen – R56.68

Although grey hydrogen remains the most cost-effective option, its price may increase in the future as a result of growing decarbonisation efforts. The 2030 price projections do not include potential carbon taxes, which could further increase the cost of fossil fuel-based hydrogen. Pink and red hydrogen could potentially be affordable in South Africa given the presence of existing nuclear power plants such as Koeberg Nuclear Plant, Western Cape, and SAFARI-1 in the North West province. However, challenges such as public perception, regulatory concerns and limited

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commercialisation may hinder cost reductions. Orange hydrogen may also offer a cost-effective alternative, particularly if coal-based electricity is integrated into the energy mix. The current cost of coal-based electricity in South Africa (as of 2024) is R2.07 per kWh, although prices vary by municipality (Eskom, 2024). Yellow hydrogen could become more affordable over time, depending on technological advancements and commercialisation efforts. However, its current high cost makes it less competitive compared to other hydrogen colours.

Hydrogen costs vary significantly based on production methods, energy sources and regional availability of resources. While grey hydrogen remains the cheapest option in South Africa, future carbon taxation policies may drive up its costs, making cleaner alternatives such as green, blue and pink hydrogen more competitive. Blue hydrogen is currently more expensive due to the use of CCUS technology, while yellow hydrogen remains the costliest as a result of technological constraints. Pink and red hydrogen could be cost-effective in South Africa because of the existing nuclear infrastructure but commercialisation challenges persist. As South Africa moves towards a hydrogen economy, cost considerations will be critical in determining the most viable hydrogen colours for different applications.

VIII SKILLS DEVELOPMENT IN ADVANCING THE MARITIME HYDROGEN ECONOMY

The growing interest in adopting a hydrogen-based economy, particularly in research, has placed significant emphasis on the skills required to support this transition. This focus extends across the entire hydrogen spectrum, assessing both existing competencies and the additional expertise needed for upskilling and reskilling. In the maritime sector, the IMO is actively pursuing decarbonisation strategies, necessitating the exclusion of darker hydrogen colours (black, brown and grey) from its sustainable fuel pathway. This exclusion aligns with global efforts to reduce GHG emissions and transition towards cleaner fuel alternatives.

The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) currently serves as a regulatory framework for alternative fuels, with a primary focus on low-flashpoint fuels such as liquefied natural gas (LNG). If all hydrogen colours were to be incorporated into this framework, the industry would need to accommodate both gaseous and liquid forms of hydrogen as viable fuel options. However, the existing IGF Code is tailored specifically to LNG (Würsig, 2024; Inal et al., 2022; Kim, Bang & Lee, 2022), which presents a critical limitation. Although some of the Code's safety principles may be applicable to hydrogen, they are not universally suitable because of hydrogen's unique properties, specifically its higher flammability and increased risk of leakage. As a result, additional regulatory frameworks and training standards are necessary. These include the IMO's forthcoming hydrogen safety regulations, ISO/TR 15916 (Basic Hydrogen Safety), (Wang et al., 2024; Moretto & Quong, 2022; Kim & Chun, 2023) and IEC 60079 (Explosive Atmospheres) (Keane et al., 2022), all of which are crucial for integrating hydrogen into the maritime sector safely.

Maritime training programmes, particularly those governed by the Standards of Training, Certification, and Watchkeeping (STCW) Convention, provide the foundational knowledge required for seafarers operating vessels that use alternative fuels. The IMO has amended the STCW to incorporate training for LNG, ammonia and methanol-fuelled vessels (Inal et al., 2022). However, given the focus of this study on the various forms of hydrogen, additional regulatory improvements are required. The Interim Guidance on Training for Seafarers on Ships Using Gaseous and Other Low-Flashpoint Fuels, adopted in January 2017, introduced amendments to the International Convention on Standards for the Safety of Life at Sea (SOLAS) under chapters II-1 and II-2 (Inal et al., 2022). While these amendments accommodate alternative fuels, they do not fully address the complexity of incorporating hydrogen into the maritime sector. The development of new training frameworks is, therefore, essential to ensure the seamless integration of hydrogen technologies, supported by an adequately skilled workforce.

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Table 4 outlines the key skill sets, training levels, target audiences and maritime job applications required to facilitate the maritime sector's transition to a hydrogen-based economy. Given the significant health and safety considerations involved in hydrogen applications, specialised training and targeted education efforts are paramount. The maritime applications presented in Table 4 are informed by research conducted by the South African Department of Higher Education and Training (DHET), which explored the skills value chain required for the green hydrogen economy (Nation, 2024). Similarly, Table 3 presents the stages of the hydrogen value chain, the corresponding skill requirements and the targeted audiences necessary for hydrogen integration within maritime operations.

This study further highlights the critical need for engineering expertise, particularly in the development of new vessels designed to accommodate hydrogen as a marine fuel, and in retrofitting existing fleets. Additionally, hydrogen-fuelled vessels require specialised logistical considerations as they move through global supply chains. Despite the promising potential of hydrogen, several challenges exist in integrating this fuel into MET institutions. The most pressing barriers include the high costs associated with implementing new courses, the need for skilled instructors capable of delivering specialised training and the time lag in curriculum development challenges that are particularly pronounced in developing economies. Although maritime operations function within an international framework, disparities in technological adoption rates may slow hydrogen integration in certain regions. Even with institutional support from organisations such as the World Maritime University, under the IMO, a substantial adaptation period will be required.

Although MET remains pivotal to the success of the hydrogen economy, it is equally critical to recognise the urgency of developing specialised skills to meet the demands of the energy transition. As the maritime sector advances towards decarbonisation, the rapid deployment of hydrogen technologies will necessitate a workforce that is both highly skilled and adaptable to emerging fuel applications.

Table 3: Indicates the stages of hydrogen economy and the skills needed and their targeted audiences

Stage	Skills Needed	Target Audience
Hydrogen Production	Electrolysis, natural gas reforming, pyrolysis, carbon capture and storage (CCS)	Engineers, chemical technologies and researchers
Hydrogen Storage	Knowledge of cryogenic storage, high-pressure systems and solid-state storage	Engineers, storage technicians and safety officers
Hydrogen Transport	Design of pipelines, tankers and other transport vessels	Engineers, chemical technologies and researchers
Bunkering	Safe handling of hydrogen and ammonia and bunkering infrastructure setup	Ship crew, bunkering specialists and port operators
Vessel Operations	Operation of hydrogen-powered ships, fuel management and system maintenance	Ship crew, technical operators and engineers
Shipbuilding	Design and construction of hydrogen-powered vessels, integration of fuel cells and ammonia engines	Naval architects, shipbuilders and engineers
Regulations	Knowledge of maritime safety regulations, hydrogen handling standards and international policies	Policymakers, maritime lawyers and regulatory bodies

Source: Authors' own work.

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Table 4: The different colours of hydrogen and the skills, training level, targeted audience and the maritime application for hydrogen

Hydrogen Colour	Key Skills	Training Level	Target Audience	Maritime Application
Grey	• SMR • Carbon emissions management • Fossil fuel transition strategies • Hydrogen distribution logistics	• Vocational • Undergraduate • Industry • Certification	• Industrial engineers • Process technicians • Maritime fuel strategists • Energy transition officers	• Navigation Engineering (marine, structural, electrical, automation, control, instrumentation) • Planning and scheduling • Information systems • Leak detection • Weather or geography analysis • Maritime law • Maritime survey • Design and fabrication • Ship management • Port management • Environmental, health and safety • Seafarers
Brown	• Coal gasification technologies • Emission mitigation strategies • Carbon capture & utilisation • Industrial process retrofitting	• Vocational • Undergraduate • Industry • Certification	• Industrial engineers • Regulatory compliance officers • Maritime fuel strategists • Environmental scientists	
Black	• Gasification technologies • High temperature • Hydrogen production • Fossil fuel reforming • Pollution control measures	• Vocational • Undergraduate • Industry • Certification	• Process technicians • Industrial engineers • Maritime energy analysts • Environmental consultants	
Blue	• Carbon capture & storage (CCS) • LNG–hydrogen blending • Infrastructure adaptation • Hydrogen transportation & storage • Life-cycle assessment	• Vocational • Undergraduate • Industry • Certification	• Ship operators • Port authorities • Energy transition officers • Environmental engineers	

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Hydrogen Colour	Key Skills	Training Level	Target Audience	Maritime Application
Green	• Electrolysis • Renewable energy integration • Fuel cell maintenance • Hydrogen bunkering • Safety and risk assessment • Regulatory compliance	• Vocational • Undergraduate • Postgraduate	• Engineers • Port Workers • Seafarers • Maritime Operators • Safety Inspectors	
Turquoise	• Methane pyrolysis • Carbon management in ports • Hydrogen derived synthetic fuels • Thermal process optimisation	• Undergraduate • Postgraduate	• Researchers • Policy Makers • Decarbonisation Consultants • Environmental Scientists	
Yellow	• Grid-integrated hydrogen production • Energy optimisation for ports • Renewable energy forecasting • Smart grid management • Demand response strategies	• Vocational • Undergraduate	• Port energy managers • Technicians • Maritime energy planners • Logistics coordinators	
Orange	• Biomass gasification • Biohydrogen production • Waste-to-hydrogen technologies • Circular economy in hydrogen production	• Undergraduate • Postgraduate • Industry • Certification	• Bioenergy specialists • Circular economy experts • Maritime fuel analysts • Environmental engineers	

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Hydrogen Colour	Key Skills	Training Level	Target Audience	Maritime Application
Pink	• Nuclear-powered hydrogen production • Nuclear safety protocols • Radiation safety in maritime applications • Supply chain logistics for nuclear hydrogen	• Postgraduate • Industry • Certification	• Nuclear engineers • Safety officers • Maritime policy makers • Regulatory authorities	
Red	• High-temperature electrolysis • Thermal energy storage • Advanced hydrogen production methods • Safety in extreme temperature processes	• Postgraduate • Research Programs	• Hydrogen Researchers • Energy Scientists • Safety Inspectors • Maritime Energy Innovators	
Hydrogen safety & regulations	• Hydrogen risk assessment • Fire & explosion safety • Maritime hydrogen fuel handling • International regulations (IMO, EU, ISO)	• Vocational • Undergraduate • Postgraduate	• Safety officers • Compliance managers • Maritime regulators • Hydrogen fuel inspectors • Seafarers	

Source: Authors' own work.

IX RESULTS AND DISCUSSION

A comparison of the median values of different hydrogen colours based on four environmental impacts eutrophication, GWP, resource depletion and acidification reveals significant disparities. Conventional hydrogen production (black, brown and grey) emerges with the highest environmental burdens, which poses challenges as industries strive to decarbonise. These conventional hydrogen types exhibit stronger impacts on acidification, eutrophication, and GWP.

Blue hydrogen and orange hydrogen, both of which use electrolysis, show a reduction in environmental impact, with blue hydrogen potentially mitigating its environmental footprint as a result of the application of CCUS. Although CCUS is not fully commercialised, it holds promise in reducing emissions from grey, black and brown hydrogen production. Studies indicate that blue hydrogen could reduce up to 70 per cent of emissions from grey hydrogen and 80 per cent from black hydrogen if CCUS is implemented effectively.

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Turquoise hydrogen, produced via pyrolysis, and green hydrogen, generated via electrolysis powered by renewable energy, show relatively lower environmental impacts. Notably, turquoise hydrogen has a higher GWP than the other impacts, making it less favourable in terms of carbon emissions. Green hydrogen, however, stands out as the most sustainable production method, with its environmental impacts primarily dependent on the source of electricity used for electrolysis. Renewable energy sources such as wind, solar and hydropower lead to the least environmental impact, positioning green hydrogen as a key technology in decarbonising industries.

The environmental data analysed also highlights black hydrogen as the highest contributor to environmental degradation, especially when coal is used as the energy source, exacerbating acidification, eutrophication and global warming. On the other hand, green hydrogen, which uses renewable energy, exhibits the lowest environmental impact across all categories. However, several barriers to the large-scale adoption of green hydrogen persist, including high costs, commercialisation challenges, technological readiness and public acceptance. Electrolysis technologies, such as PEM and alkaline electrolysis, are well established but still face cost and scalability issues. SOEs, while efficient at high temperatures, are not yet commercially viable at scale. It is important to note that the environmental impact results sourced from different literature might vary due to differences in life-cycle analysis scope, such as whether transportation was included or excluded. In terms of acidification, eutrophication and global warming, black hydrogen remains the highest emitter, with grey hydrogen showing the highest resource depletion. Brown hydrogen stands out for its acidification potential, which may compromise land and water resources.

The costs of each hydrogen colour further emphasise the affordability of conventional hydrogen (grey, black, brown), with grey hydrogen being the least expensive. However, as carbon taxes increase, the prices of these conventional hydrogen types could rise, creating opportunities for green hydrogen to become more competitive. The cost of production for green, yellow and pink hydrogen remains high, primarily due to the immature state of their technologies and the need for large-scale commercialisation. As for TRL, conventional hydrogen methods are at TRL 9, reflecting their widespread commercial adoption and maturity (Thomas, 2019). However, technologies for green hydrogen face challenges related to the readiness of electrolysis systems and the availability of electrolysers, particularly PEM technology, which is the most commonly used in South Africa. In contrast, blue hydrogen and turquoise hydrogen are still emerging, with CCUS technology being in its early stages (TRL 1–3) and pyrolysis still not fully developed at commercial scale.

In South Africa, grey, black and brown hydrogen technologies are well established but the country faces challenges in scaling up cleaner technologies such as green hydrogen. Including PEM electrolysis at TRL 9, the technology is ready but needs further investment in research, development and commercialisation to lower costs. Although, green hydrogen shows better environmental performance, it has lower TRL maturity and higher costs compared to conventional methods. Conversely, grey hydrogen, with its higher TRL maturity and economic viability, performs well from a cost perspective but at the expense of environmental impact. Technologies such as blue hydrogen and turquoise hydrogen show promise but remain in the early development stages in South Africa.

Although the IGF Code provides existing training standards, it does not currently accommodate the hydrogen economy in the maritime industry. It is, therefore, essential for the IMO to either introduce a dedicated framework or amend the existing standards to ensure hydrogen's integration into maritime operations. Beyond regulatory adjustments, the industry requires significant skills development, including upskilling, reskilling, and the introduction of specialised courses to support the hydrogen transition. Engineering remains a critical discipline for hydrogen applications in the sector, not only for vessel design and retrofitting but also across the entire maritime hydrogen value chain, ensuring a comprehensive and sustainable adoption of this alternative fuel.

This study suggests that green hydrogen should focus on research and development to reduce production costs

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and enhance technology performance. Investment in electrolysis systems, improved material efficiency, and scaling up renewable energy sources will be critical to achieving large-scale, sustainable hydrogen production in South Africa and beyond.

X CONCLUSION

In conclusion, this study provides a comprehensive overview of the various hydrogen production methods, identified by their corresponding colours: grey, black, brown, blue, green, turquoise, pink, red, yellow and orange. It evaluated the costs, TRL and environmental impacts (GWP, acidification, eutrophication and resource depletion) associated with each colour of hydrogen. The findings highlight the situation that hydrogen technologies that are not yet commercialised or produced at large scale (green, yellow and pink) are relatively expensive, despite their superior environmental benefits compared to the conventional hydrogen types (black, grey and brown). On the other hand, the more mature and affordable technologies, such as grey, black and brown hydrogen, pose significant environmental challenges. While these conventional methods are cost-effective, they contribute significantly to environmental degradation, particularly in terms of acidification, eutrophication and GWP. The study also revealed that blue hydrogen, when coupled with CCUS, could play a critical role in mitigating CO_2 emissions from conventional hydrogen production. However, this solution appears to be more of a temporary measure rather than a long-term fix, given the ongoing infancy of CCUS technology. However, the current cost of less mature technologies such as green hydrogen, yellow hydrogen, and pink hydrogen remains high, these technologies hold promise for sustainability and environmental performance in the long run. The key to improving their affordability lies in reducing the costs of electrolysis and further advancing these technologies to a commercial scale. Although black hydrogen may be economically attractive in the short term, its environmental cost is substantial, which further emphasises the need for sustainable alternatives. Blue hydrogen offers a potential bridge by addressing the environmental impact of conventional hydrogen production methods but its role as a permanent solution remains uncertain without full commercial-scale implementation of CCUS. Skills development is fundamental for the successful integration of the hydrogen economy in the maritime industry's decarbonisation efforts. A well-structured approach to upskilling and reskilling, and the introduction of new competencies will be essential to support the transition towards hydrogen-based fuels and ensure the industry's sustainability in the evolving energy landscape. Moving forward, future research should focus on the potential of these emerging hydrogen technologies, especially for developing countries such as South Africa, which face unique challenges in energy production and infrastructure. A deeper exploration of how these new technologies can be scaled, integrated and optimised for local conditions will be critical to achieving sustainable hydrogen production at a global level. This study emphasises the importance of further investigation into the relationship between the environmental impacts, technological readiness, and cost structures of the various hydrogen production methods, offering a more transparent and comprehensive understanding of their potential for a sustainable future.

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