The UUPO project – New fuels for maritime logistics as drivers of green transition and blue growth

Fuel Info Package: Hydrogen

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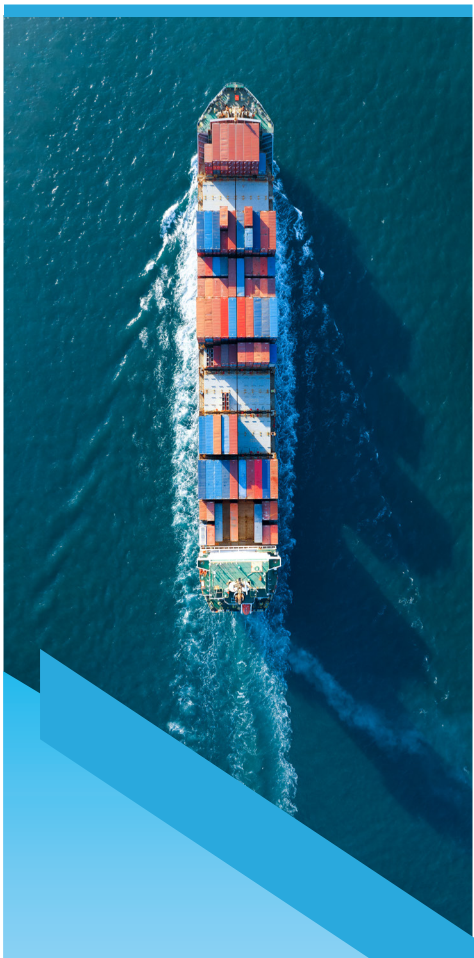
Satakunta University of Applied Sciences

SATAKUNTALIITTO

Regional Council of Satakunta

2024

Basic information



Important notes:

1. Hydrogen is a carbon-free fuel, meaning its use does not result in carbon-based greenhouse gas emissions.

2. Hydrogen itself is not a greenhouse gas, but in the atmosphere, it can indirectly contribute to climate warming.

3. Storing hydrogen is highly challenging, and its use involves significant fire and explosion hazards.

4. Hydrogen's low energy density may limit its use primarily to shorter distances and sea routes.

5. The broader use of hydrogen requires the creation of entirely new infrastructure and distribution chains

Hydrogen

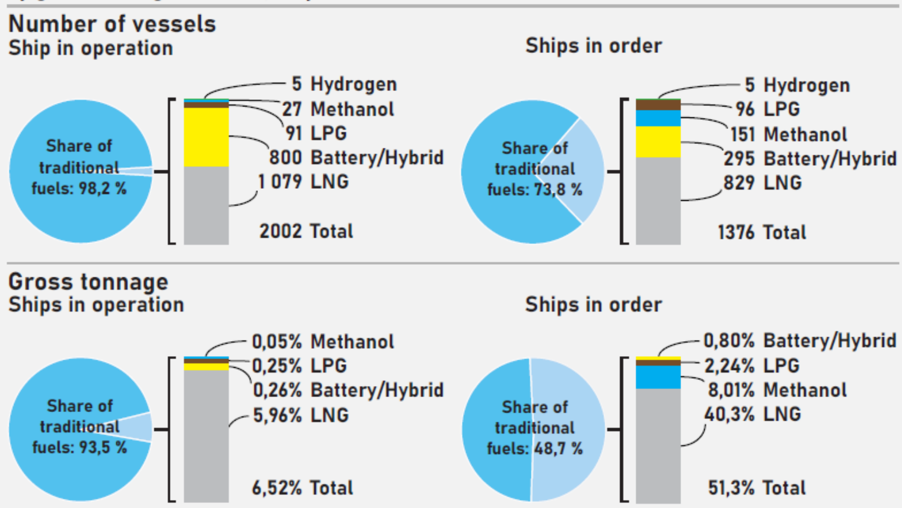
Hydrogen (H) is the simplest and most common element in the universe, consisting of a single proton and electron. At normal temperature and pressure, hydrogen is a light, colorless, and odorless gas. Although hydrogen is extremely common, it is rarely found as a free gas due to its reactivity, which causes it to be bound in various compounds with other elements. [1]

Hydrogen currently plays a vital role across various industries, including chemical manufacturing, steel production, and other industrial processes. [2]

In the future, hydrogen production and use are expected to change significantly, as many new synthetic fuels will require hydrogen as a raw material. Hydrogen itself will also most likely be used more widely as a fuel, both in combustion engines and fuel cells. The advantage of using hydrogen as a fuel is its carbon-free nature, meaning its combustion or use produces no carbon dioxide, and under optimal conditions, the only byproduct of the combustion reaction is water. Additionally, hydrogen can be produced through carbon-neutral methods, enabling very low lifecycle emissions. As global industries aim to achieve net-zero emissions, hydrogen's potential role in various sectors, from maritime to heavy transport, becomes increasingly critical. Furthermore, the flexibility in production sources allows hydrogen to integrate seamlessly into renewable energy systems, enhancing energy resilience and sustainability.

Although hydrogen has great potential as a clean marine fuel, several factors complicate its adoption. These factors include a lack of infrastructure, fire safety risks, low energy density, and challenges related to storage and transportation.

Figure 1. Adoption of alternative fuels in the global fleet by the number of vessels (top) and by gross tonnage (bottom), July 2023



Citations: [1], [2], [Figure 1]

Production methods

Hydrogen can be produced in many different ways and is typically classified into different color categories based on the production process and the raw materials used.

Grey hydrogen

Grey hydrogen is produced by steam reforming natural gas. In the steam reforming process, natural gas is heated with steam in the presence of a catalyst, causing the natural gas and steam to react. The result of the reaction is synthetic gas, mainly composed of carbon monoxide and hydrogen. The carbon monoxide is often further processed using the water-gas shift reaction, where carbon monoxide and steam react to produce carbon dioxide and more hydrogen. Hydrogen is separated from carbon-based gases and other impurities through pressure swing adsorption, resulting in virtually pure hydrogen. [3]

Grey hydrogen is by far the most common way to produce hydrogen, accounting for about 62% of the world's total hydrogen production in 2022. [4]

Black and brown hydrogen

Black and brown hydrogen typically refer to hydrogen produced from either coal or lignite. Both types of hydrogen are obtained through a coal gasification process. In this process, coal or lignite is heated to high temperatures in the presence of oxygen, air, or steam. As a result, the carbon in the raw material partially oxidizes, producing synthesis gas. The produced synthetic gas can be further refined in the same way as the synthetic gas in grey hydrogen production. [5]

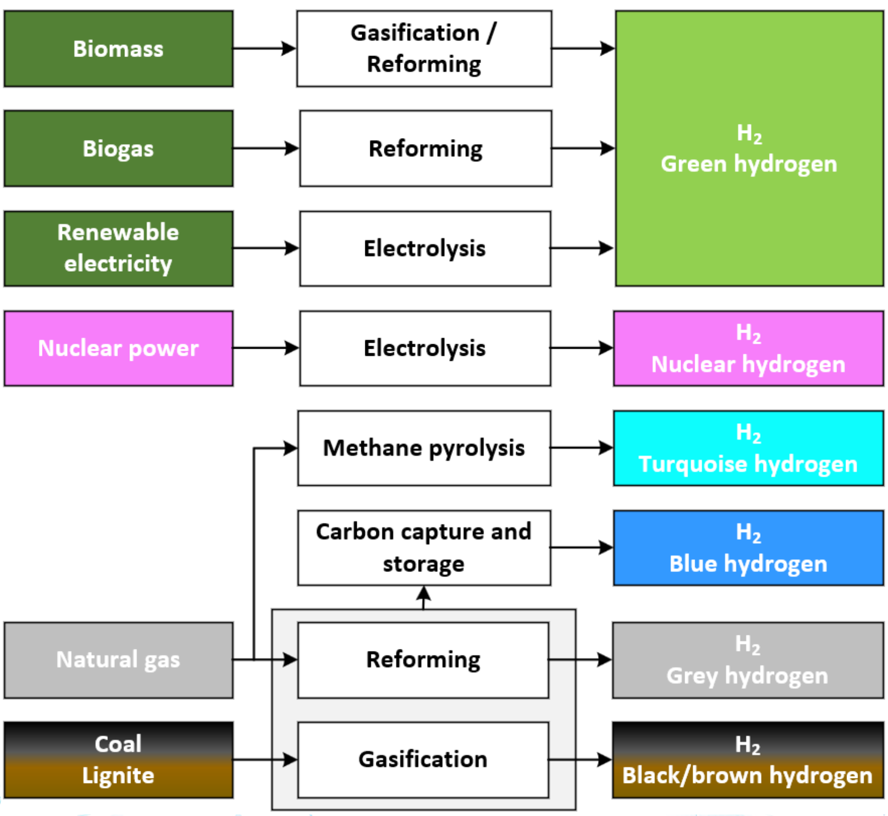
Black and brown hydrogen are the most environmentally harmful methods of hydrogen production, as they generate significant amounts of greenhouse gas emissions. [6]

In 2022, black and brown hydrogen accounted for about 21% of the world's hydrogen production. [7]

Blue hydrogen

Blue hydrogen is produced using the same production processes as grey, black, and brown hydrogen, but the greenhouse gas emissions generated during the process are partially prevented from entering the atmosphere through various technological solutions. Examples include carbon capture, where the produced emissions are captured and stored in geological formations. The captured carbon dioxide can also be used in various processes, such as the production of synthetic fuels. In 2022, about 0,6% of hydrogen was produced from fossil raw

Figure 2. The main methods for producing hydrogen



Production methods

materials using carbon capture technologies. [8]

While blue hydrogen appears promising in theory, a 2021 study found that blue hydrogen's carbon dioxide equivalent emissions were only about 9–12 % lower compared to grey hydrogen. This was primarily due to methane leaks, which were observed in large quantities during blue hydrogen production because natural gas was often used as an energy source for carbon capture processes. This finding raises questions about the environmental friendliness of blue hydrogen and its ability to significantly reduce emissions compared to other hydrogen production methods. [9]

Green hydrogen

Green hydrogen is typically produced by splitting water molecules into their components using renewable electricity and electrolysis. The most common electrolysis technologies are alkaline, PEM, and steam electrolysis. [10]

Hydrogen produced via electrolysis does not generate any carbon dioxide emissions, making it an environmentally friendly alternative compared to other production methods. However, challenges arise from the large amount of energy required for the electrolysis process, of which only part can be used to produce hydrogen. In an electrolysis plant, about 60 % of the electricity can be converted into the chemical energy of hydrogen, while 30 % of the electrical energy is lost as waste heat. The remaining electricity is completely wasted. [11]

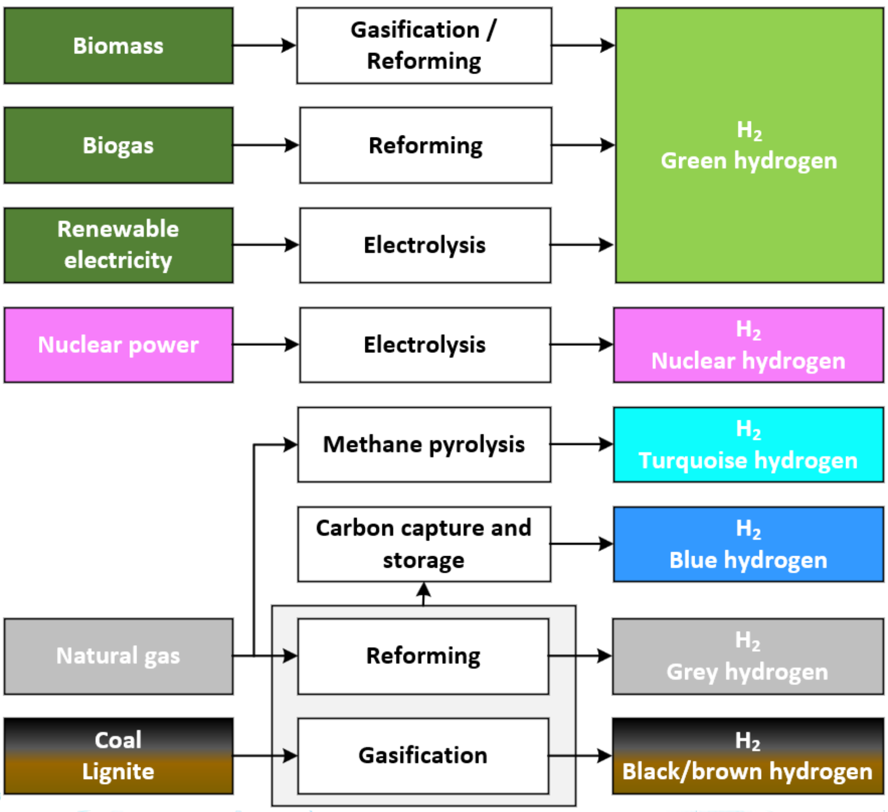
The overall efficiency of the process is relatively low unless the waste heat is utilized. Other problems for green hydrogen may include the availability of fresh water and electrolyzers. [12] All these challenges can significantly affect the cost and growth of green hydrogen, especially in areas where renewable energy resources are scarce and fresh water is limited.

In addition to electrolysis, green hydrogen can be produced by gasifying biomass or reforming biogas. [13]

Pink hydrogen

Pink hydrogen can be produced through electrolysis, but unlike green hydrogen production, the energy source is electricity generated from nuclear power instead of renewable electricity. Since electricity produced from nuclear power is practically carbon-free, this also enables low-emission hydrogen production. [14]

Figure 2. The main methods for producing hydrogen



Production methods

Turquoise hydrogen

Turquoise hydrogen is produced similarly to grey hydrogen, using natural gas. The difference between these production methods is that in turquoise hydrogen, natural gas is split into its components using pyrolysis. In this process, the end products are hydrogen and solid carbon, allowing the carbon to be easily captured and stored. This significantly reduces the greenhouse gas emissions of the process compared to grey hydrogen. However, turquoise hydrogen is still a relatively new way to produce hydrogen, and commercial-scale demonstration plants are only now being built. [15]

White hydrogen

White hydrogen is not directly produced from any process but is naturally occurring hydrogen stored in underground formations. However, extracting it is challenging, and the formations may also contain other harmful gases, which could contribute to climate warming. Currently, white hydrogen is not utilized anywhere, but this may change, as in 2023, a significant hydrogen deposit was reported in France. The deposit's size was approximately 46 Mt, or nearly half of the world's current annual hydrogen production. The discovery was made during the Regalor project, and due to the deposit's impact, the project was continued with the aim of finding ways to utilize this hydrogen. [16]

Other production

A substantial amount of hydrogen is also produced as a byproduct in various industries. Notably large quantities come from the fuel industry, where it is often used in the internal operations of refineries, such as in hydrogen cracking and sulfur removal processes. In 2022, byproduct hydrogen made up approximately 16 % of total hydrogen production. [17]

Citations: [14], [15], [16], [17]

Properties and safety aspects

Fuel properties

The heating value of liquid hydrogen (L H2) is clearly the highest of all fuels. It is approximately three times greater compared to traditional fossil fuels, such as diesel and heavy fuel oil, which have an effective calorific value of around 40 MJ/kg. However, it is important to understand that due to the extremely low density of liquid hydrogen, its energy content relative to volume is very low. Compared to fuel oil, hydrogen requires about five times the space for the same amount of energy. [18]

The high autoignition temperature of hydrogen makes its use in internal combustion engines challenging. In practice, this means that when hydrogen is used in an internal combustion engine, relatively high pressures and temperatures are needed in the combustion chambers, which can cause additional stress on the engine and other components. [19]

However, hydrogen has some positive fuel properties. For example, it has a wide flammability range, meaning it can be burned with a wide fuel-air ratio. This also makes engine starting easier. Additionally, due to its high flame front speed and diffusion capability, hydrogen burns more efficiently and cleaner than many other fuels. [20]

Safety aspects

Compared to other fuels, one of hydrogen's advantages is its non-toxicity to humans and other organisms. However, due to the extremely low temperature of liquid hydrogen, frostbite injuries can occur. [21]

Although hydrogen is relatively non-toxic as a fuel, its use involves significant fire and explosion hazards. Due to its wide flammability range, hydrogen can form a flammable gas mixture with air even in small quantities. Under optimal conditions, the ignition energy of a hydrogen-air mixture is about one-fifteenth of that of gasoline. [22] For this reason, handling and storing hydrogen requires special safety measures and careful monitoring. In maritime transport, the use of hydrogen as fuel requires the development of new safety protocols and technologies to reduce risks and ensure safe operation.

	Energy and storage					Flammability		
Fuel	Density [kg/m^3]	Lower heating value [MJ/kg]	Energy density [MJ/m^3]	Boiling point [°C]	Fuel volume requirement vs. LSHFO	Autoignition temperature in air [°C]	Flashpoint [°C]	Flammability limits in air [%]
LSHFO	993	40,5	40 217	> 180	-	230	> 60	0,6 - 7,5
MDO	819	40,5	33 170	> 180	1,21	210	> 60	0,6 - 7,5
LNG	450	49,1	22 095	-162	1,82	540	-188	5,0 - 15,0
MeOH	792	19,9	15 761	65	2,55	464	12	6,7 - 36,0
EtOH	789	26,8	21 145	78	1,90	365	17	3,3 - 19,0
L NH_3	680	18,6	12 648	-33	3,18	651	132	15,0 - 28,0
L H_2	**70**	**120**	**8 400**	**-253**	**4,79**	**585**	**-**	**4,0 - 75,0**
FAME	880	37,2	32 736	> 180	1,23	261	> 61	0,6 - 7,5
HVO	780	44	34 320	> 180	1,17	204	> 61	0,6 - 7,5
FT-Diesel	785	43,2	33 912	> 180	1,19	204	89	0,6 - 7,5

Citations: [18], [19], [20], [21], [22], [Table]

Production

Global production

According to IEA estimates, the global annual hydrogen production was about 90 Mt in 2020. By 2022, production had increased to approximately 95 million tons, indicating an annual growth of about 3 percent between 2020 and 2022. A significant majority of this hydrogen was produced through steam reforming of natural gas, followed by the gasification of coal as the second most common production method. Although the share of low-emission hydrogen production is currently less than one percent of total production, its capacity is expected to grow significantly by 2030. The production capacity of publicly announced low-emission hydrogen production projects was estimated to be about 20 Mt in 2023, and when including projects in early stages, this figure rose to 38 million tons. Most of this production will occur through electrolysis. [23]

Production can also occur outside large facilities. In 2023, the French company Lhyfe demonstrated that hydrogen can be generated at sea using a floating production facility that harnesses offshore wind energy. In the future, ships could readily utilize hydrogen produced in this way. [24]

According to DNV estimates, global hydrogen demand in 2050 will exceed 300 Mt per year, while the IEA has projected this demand to be around 400 Mt. [25] [26] Some estimates suggest that hydrogen demand in 2050 could be as high as about 500 Mt. [27]

Future outlooks in Finland and Satakunta

In Finland, approximately 145 000 tons of hydrogen were produced in 2020, most of which was generated through steam reforming. Additionally, hydrogen was produced as a byproduct from various industrial processes, amounting to about 20 000 tons. The largest consumers of hydrogen were oil refineries and biofuel producers. [28]

Hydrogen production in Finland is expected to increase significantly in the coming years. Several projects in the planning phase are worth billions of euros in investments. The largest projects are backed by the American company Plug Power, which plans to build three green hydrogen production plants in Kokkola, Kristiinankaupunki, and Porvoo. However, these projects are still in the planning phase, and the final investment decision will be made only during 2025 and 2026. [29]

The largest demonstration production facility for turquoise hydrogen in Europe is also being planned in Kokkola, which would have the capacity to produce approximately 2 000 tons of hydrogen annually. [30]

Furthermore, hydrogen production is being investigated in the Bothnian Sea, where the renewable energy generated by vast offshore wind farms could be utilized for hydrogen production. [31]

Some of these projects focus on producing clean hydrogen for use in various processes and as fuel. In contrast, other projects will utilize the produced hydrogen for the manufacture of synthetic fuels, such as methanol, ammonia, and methane.

Hydrogen production in Satakunta also looks promising, as P2X Solutions is set to begin green hydrogen production in Harjavalta in 2024 at Finland's first green hydrogen production plant. [32] Ren-Gas, on the other hand, plans to build a green hydrogen production facility near the bioenergy plant in Pori, with production estimated to start in 2027. [33] Green North Energy has also conducted feasibility studies for constructing a hydrogen production facility in Pori. [34] Additionally, studies on the possibilities of a hydrogen economy have been conducted in the Rauma area. [35]

Although green hydrogen production looks promising, it is important to note that if the entire Finnish maritime fleet were to switch to using green hydrogen as fuel, producing it through electrolysis would require about 59 TWh of electricity, taking into account the losses from electricity transmission. [36] This corresponds to approximately 75 % of the current electricity production in Finland. [37]

Citations: [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37]

Technical aspects

Infrastructure

In hydrogen infrastructure, the behavior of hydrogen in relation to various materials must always be considered. While hydrogen is not directly a corrosive substance, it can embrittle various metals and materials. Hydrogen embrittlement occurs because hydrogen's small atomic size allows it to penetrate deep into the metal's structure. The structure of metals primarily consists of small crystals, and during hydrogen embrittlement, hydrogen accumulates in the spaces between these crystals, reducing the metal's elasticity and tensile strength. This can ultimately lead to a weakening of the metal's strength and potential structural failure. [38] Without proper design and material selection, hydrogen embrittlement can cause serious problems in storage containers, pipelines, or other components handling hydrogen. Therefore, it is crucial to consider the risks associated with hydrogen embrittlement and fire safety and to apply appropriate safety standards and practices in the design and operation of hydrogen infrastructure. [39]

One of hydrogen's major weaknesses is that it cannot be directly used in fossil fuel infrastructure. The broader use of hydrogen practically requires the creation of a completely new infrastructure and distribution chain, complicating and slowing its adoption in maritime logistics. [40]

Transportations and storage

Pure hydrogen is transported in both compressed and liquid forms in various ways. Larger quantities of compressed hydrogen are typically transported through pipelines, while smaller needs, such as for refueling stations, use tank trucks. [41]

The advantages of transporting compressed hydrogen include the fact that there are currently over one million kilometers of natural gas pipelines worldwide. These pipelines can be modified to suit hydrogen transport as natural gas transmission and usage decline. Globally, there are about 5 000 km of pipelines constructed specifically for hydrogen. [42] Liquid hydrogen, on the other hand, is transported by ships and tank trucks, ensuring that the liquid hydrogen remains below its boiling point temperature. [43]

Additionally, hydrogen can be transported in various compounds, such as ammonia, where ammonia effectively serves as a hydrogen carrier. In this transport method, ammonia is first produced using hydrogen and nitrogen. It is then transported to the destination, where it is cracked back into hydrogen and nitrogen. The advantage of this transport method is that ammonia is significantly easier to transport due to its energy density and higher boiling point. However, the production and cracking of ammonia require energy. [44]

Storing hydrogen poses challenges, as it must be stored as a gas at relatively high pressures or as a liquid at very low temperatures. Currently, gaseous hydrogen storage may occur at pressures up to 700 bar. Liquid storage requires cryogenic tanks that continuously cool the hydrogen to prevent the temperature from rising above the boiling point. [45] The storage challenge is further complicated by hydrogen's ability to penetrate through the walls of storage tanks, leading to potential leaks and safety risks. [46]

Due to hydrogen's low energy density, the size of these storage tanks is significantly larger compared to traditional fossil fuels if the same amount of energy is to be stored. [47]

Many organizations and experts believe that ports will play a key role in the growth of the hydrogen economy. Ports will serve as hubs for hydrogen infrastructure, enabling the arrival and departure of hydrogen-carrying vessels and the handling and conversion of liquid hydrogen into gaseous form. [48]

Citations: [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48]

Technical aspects

Use as fuel

Most current vehicles that use hydrogen as a power source operate using hydrogen fuel cells, which convert hydrogen directly into electricity. Hydrogen fuel cells generate also a significant amount of heat, which can be effectively utilized for heating passenger areas on ships, for example. Often, various types of battery systems are used alongside hydrogen fuel cells.

Hydrogen fuel cell vehicles are available from various manufacturers, including Hyundai and Toyota. Hyundai has also demonstrated the functionality of fuel cells in heavy-duty transport and supplied 10 fuel cell-powered trucks to Switzerland in 2020. [49]

Hydrogen has also proven to be a viable alternative in rail transport. In August 2022, Germany introduced 14 hydrogen-powered fuel cell trains. However, the following year, the Ministry of Transport announced that the trains would switch to using electricity and batteries for economic reasons. [50] Although the trains were in use for only a year, they still demonstrated that hydrogen could serve as an energy source for rail transport.

In addition to land and rail transport, hydrogen has begun to be utilized in maritime transport. In 2023, SWITCH Maritime began operating an 80-passenger ferry powered by hydrogen fuel cells in the San Francisco Bay area of the United States. In the same year, Norway launched the MF Hydra, a hydrogen fuel cell-powered vehicle and passenger ferry. MF Hydra operates on the Hjelmeland-Skipavik-Nesvik route and can carry approximately 300 passengers and 80 vehicles. The total power output of the fuel cells on the U.S. ferry is about 360 kW, while MF Hydra's fuel cell power output is reported to be 400 kW. [51] [52]

Hydrogen is also being used for freight transport, for example, in Western Europe's inland waterways. The H2 Barge 1 is a barge equipped with a 900 kW hydrogen fuel cell operating between the ports of Rotterdam in the Netherlands and Meerhout in Belgium. The vessel was originally named FPS Maas and operated with a conventional combustion engine before being converted to operate on hydrogen fuel between 2022 and 2023. [53]

More extensive plans for hydrogen-powered vessels are being developed by the Danish shipping company DFDS. In 2021, they announced intentions to build a hydrogen fuel cell cruise ship capable of carrying approximately two thousand passengers on the Oslo-Fredrikshavn-Copenhagen route. However, a significant challenge in constructing the vessel is the required power of 23 000 kilowatts, as fuel cell systems of this size are not yet implemented in any maritime vessels. [54]

In addition to fuel cell solutions, hydrogen internal combustion engines are being researched and developed. For example, MAN Energy Solutions announced a hydrogen internal combustion engine for agricultural machinery at the end of 2023. [55] The company also reported a successful laboratory test in March 2024, in which they tested their two-stroke hydrogen internal combustion engine designed for marine use. [56]

While hydrogen is not yet widely used in maritime transport, advances in other sectors, such as land and rail transport, could facilitate its adoption in maritime transport as well. Moreover, extensive research is being conducted on the use of hydrogen in ships, so it is only a matter of time before hydrogen begins to be utilized more in maritime transport. However, it is important to note that due to hydrogen's low energy density, its use is likely to be more limited to shorter distances and smaller vessels.

Citations: [49], [50], [51], [52], [53], [54], [55], [56]

Environmental aspects

Hydrogen is likely to play a significant role in the green transition of maritime logistics, providing a sustainable alternative to traditional fuels. Its use as a fuel produces significantly fewer emissions compared to almost any other fuel. Additionally, hydrogen can be produced from renewable energy sources, such as solar and wind power, which reduces dependence on fossil fuels and lowers maritime emissions.

However, it is essential to consider hydrogen's weaknesses regarding the environmental aspects of its use and production.

Greenhouse gas emissions

The use of hydrogen as a fuel does not produce any greenhouse gases other than water vapor. The impact of water vapor on climate warming is complex and different from many other greenhouse gases. Most greenhouse gases, such as carbon dioxide and methane, remain in the atmosphere in gaseous form, whereas water vapor can transition from gas to liquid and leave the atmosphere relatively quickly. This means that the water vapor produced by humanity does not contribute significantly to climate warming compared to carbon dioxide, for example. [57]

Recent studies have shown that although hydrogen itself is not a greenhouse gas, it can still affect climate warming. This is because hydrogen reacts with hydroxyl radicals (OH) in the atmosphere, forming various compounds. Hydroxyl radicals also play a key role in the removal of methane from the atmosphere, and increased hydrogen in the atmosphere can theoretically slow down the removal of methane by consuming hydroxyl radicals through reactions with hydrogen, thus making them unavailable for breaking down methane. Therefore, it is critical that as little hydrogen as possible escapes into the atmosphere during its production, transportation, storage, and use. This is relatively challenging since hydrogen is a very small molecule that can easily leak through even small cracks and pores. However, the effects of hydrogen on climate warming still require further research to gain a better understanding of its actual impacts. [58]

Additionally, it is worth noting that significant amounts of greenhouse gas emissions can arise from hydrogen production if the hydrogen is produced from fossil-based raw materials.

Nitrogen oxides emissions

Hydrogen fuel cells do not produce nitrogen oxides, but, like other combustion engines, hydrogen combustion engines generate NOx emissions when atmospheric nitrogen reacts with oxygen at high temperatures. [59]

Sulfur oxides emissions

Hydrogen does not contain sulfur, so it does not produce any sulfur oxides. However, these emissions may occur if pilot fuels are used in the combustion engine. [60]

Other emissions

Hydrogen does not produce other emissions, such as particulate matter or VOC emissions. However, any potential pilot fuels may produce various emissions depending on the type of pilot fuel used. [61]

Fuel spills

Hydrogen fuel spills do not pose large environmental problems since hydrogen is the lightest of all gases, meaning it rises quickly to the upper layers of the atmosphere and disperses. Additionally, hydrogen is non-toxic and does not pose direct risks to health or vegetation. [62]

Citations: [57], [58], [59], [60], [61], [62]

Summary

Hydrogen is not yet widely used in maritime transport and is viewed, like ammonia, more as a future fuel due to the significant challenges still associated with its use. For instance, issues related to the storage and distribution of hydrogen must be resolved before it can be more broadly utilized as a fuel. Safety considerations are also crucial, as hydrogen is highly flammable and requires careful monitoring and specific arrangements to mitigate explosion risks. The impact of hydrogen on climate change is not yet fully understood, necessitating further research in this area. Additionally, due to its energy density, hydrogen is currently regarded primarily as a fuel for short distances and inland waterways, rather than as a power source for deep-sea shipping.

Currently, hydrogen production also generates significant greenhouse gas emissions, although the production of green hydrogen is becoming increasingly common. Existing electrolyzers often require various rare minerals, which may have limited availability and be subject to geopolitical tensions, as well as fluctuations in market prices. The supply chain for these minerals may also involve other challenges, such as environmental impacts and social issues. However, electrolyzer technology is rapidly evolving, suggesting that more widely available materials may be used in the future.

Despite the challenges, hydrogen has many advantages, as it can significantly reduce emissions in maritime transport. It is clear that hydrogen will play a significant role in the future of shipping, either directly as a fuel or as a raw material for synthetic fuels.

Strengths

+ Hydrogen use in internal combustion engines does not produce any carbon-based greenhouse gas emissions
+ Hydrogen can be produced using carbon-neutral methods
+ It is non-toxic to humans, organisms, or the environment
+ Natural gas pipelines can be converted to be suitable for hydrogen as natural gas usage decreases
+ Hydrogen does not produce any SOx or particulate emissions
+ Hydrogen fuel cells do not emit any pollutants
+ In the future, hydrogen may be captured from geological storage

Weaknesses

- Hydrogen is not yet in use in shipping, so the standards and practices related to its use are still in development
- Hydrogen distribution and storage are very challenging
- There are various fire and explosion safety risks associated with hydrogen use
- Increased hydrogen in the atmosphere may contribute to climate change
- Hydrogen has the lowest energy density of all fuels, meaning its storage requires a lot of space
- Existing fossil fuel infrastructure cannot be utilized without significant changes
- In the electrolysis process, only a portion of the electrical energy can be converted into the chemical energy of hydrogen
- Most hydrogen is currently produced from fossil raw materials

References

[1] Jolly, W. L. (n.d.). Reactivity of hydrogen. Retrieved 23.05.2024 from: https://www.britannica.com/science/hydrogen/Reactivity-of-hydrogen

[2] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (pp. 21-22). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[3] Department of Energy. (n.d.). Hydrogen Production: Natural Gas Reforming. Retrieved 23.05.2024 from: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

[4] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (p. 64). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[5] Metropolitan Washington Council of Goverments. (n.d.). Fact sheet series: Hydrogen production from coal. Retrieved 23.05.2024 from: https://www.mwcog.org/file.aspx?&A=6lJMMDOHmOUL2TT9fb7pcrAAeY5PdpMxMeZbS9eJzyo%3D

[6] DNV. (2022). Hydrogen forecast to 2050. (p. 49). Retrieved 23.05.2024 from: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/

[7] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (p. 64). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[8] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (p. 64). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[9] Howarth, R. W., & Jacobson, M. W. (2021). How green is blue hydrogen? Retrieved 23.05.2024 from: https://onlinelibrary.wiley.com/doi/10.1002/ese3.956

[10] Lahtinen, L. (2019). Vedyn tuotanto pienen kokoluokan elektrolyysilaitteilla. (p. 8). Retrieved 23.05.2024 from: https://lutpub.lut.fi/bitstream/handle/10024/159332/Kandidaatinty%C3%B6_Lahtinen_Lauri.pdf?sequence=1&isAllowed=y

[11] Juuti, P. (2022). Biovoimalan päästöistä ja vedystä tehtiin onnistuneesti polttoainetta Keravalla – se on uusi ja tarpeellinen keino ilmastokriisin hillitsemisessä. Retrieved 23.05.2024 from: https://yle.fi/a/3-12265099

[12] Joukanen, T. (2023). Maailman ensimmäinen vihreän vedyn tuotantolaitos avomerellä läpäisi testit – Suomeen on suunnitteilla tuotantoa Perämerelle. Retrieved 23.05.2024 from: https://yle.fi/a/74-20062706

References

[13] Ringsgwandi, L. M., Schaffert, J., Brücken, N., Albus, R, & Görner, K. (2022). Current Legislative Framework for Green Hydrogen Production by Electrolysis Plants in Germany. (p. 4). Retrieved 23.05.2024 from: https://www.researchgate.net/publication/358926929_Current_Legislative_Framework_for_Green_Hydrogen_Production_by_Electrolysis_Plants_in_Germany

[14] National Grid. (2023). The hydrogen colour spectrum. Retrieved 23.05.2024 from: https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum

[15] Sánchez-Bastardo, N., Schlögl, R., & Ruland, H. (2021). Methane Pyrolysis for Zero-Emission Hydrogen Production: A Potential Bridge Technology from Fossil Fuels to a Renewable and Sustainable Hydrogen Economy. Retrieved 23.05.2024 from: https://pubs.acs.org/doi/10.1021/acs.iecr.1c01679

[16] King, L. (2023). Is France home to the world's largest deposit of natural hydrogen? (2023). Retrieved 23.05.2024 from: https://hydrogentoday.info/en/natural-hydrogen-france-lorraine/

[17] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (p. 64). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[18] Bertagna, S., Kouznetsov, I., Braidotti, L., Marino, A., & Bucci, V. (2023). A Rational Approach to the Ecological Transition in the Cruise Market: Technologies and Design Compromises for the Fuel Switch. (p. 4). Retrieved 23.05.2024 from: https://www.researchgate.net/publication/366818830_A_Rational_Approach_to_the_Ecological_Transition_in_the_Cruise_Market_Technologies_and_Design_Compromises_for_the_Fuel_Switch

[19] Salahi, M. M., Andwari, A. M., Könnö, J., Gharehghani, A. (2022). Hydrogen and ammonia fuelled internal combustion engines, a pathway to carbon-neutral fuels future. (p. 34). Retrieved 23.05.2024 from: https://oulurepo.oulu.fi/bitstream/handle/10024/33759/nbn-fi-fe2022120970382.pdf?sequence=1&isAllowed=y

[20] College of the Desert. (2001). Hydrogen Use In Intrenal Combustion Engines. (p. 3-3). Retrieved 23.05.2024 from: https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf

[21] Hydrogen Association. (n.d.). Fact sheet series: hydrogen safety. (p. 2). Retrieved 23.05.2024 from: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_safety_fsheet.pdf

[22] Hydrogen Association. (n.d.). Fact sheet series: hydrogen safety. (p. 2). Retrieved 23.05.2024 from: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_safety_fsheet.pdf

[23] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (pp. 64-66). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

References

[24] Joukanen, T. (2023). Maailman ensimmäinen vihreän vedyn tuotantolaitos avomerellä läpäisi testit – Suomeen on suunnitteilla tuotantoa Perämerelle. Retrieved 23.05.2024 from: https://yle.fi/a/74-20062706

[25] DNV. (2022). Hydrogen forecast to 2050. (p. 71). Retrieved 23.05.2024 from: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/

[26] International Energy Agency. (2023). Global hydrogen demand in the Net Zero Scenario, 2022-2050. Retrieved 09.10.2024 from: https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-in-the-net-zero-scenario-2022-2050

[27] International Chamber of Shipping. (2024). New hydrogen demand report unveils once in a generation opportunity. Retrieved 09.10.2024 from: https://www.ics-shipping.org/press-release/new-hydrogen-demand-report-unveils-once-in-a-generation-opportunity/

[28] Sivill, L., Bröckl, M., Semkin, N., Ruismäki, A., Pilpola, H., Laukkanen, O., Lehtinen, H., Takamäki, S., Vasara, P., & Patronen, J. (2022). Vetytalous – mahdollisuudet ja rajoitteet. (pp. 111-112). Retrieved 23.05.2024 from: https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/163901/VNTEAS_2022_21.pdf

[29] Lindholm, P., & Halla-Aho, E. (2023). Suomi on saamassa uuden miljardi-investoinnin: Amerikkalaisyhtiö suunnittelee Suomeen kolmea vedyntuotantolaitosta. Retrieved 23.05.2024 from: https://yle.fi/a/74-20034105

[30] Martin, P. (2024). Construction begins at Europe's largest turquoise hydrogen facility. Retrieved 23.05.2024 from: https://www.hydrogeninsight.com/production/construction-begins-at-europe-s-largest-turquoise-hydrogen-facility/2-1-1586206

[31] Vihanta, A. (2022). Kilpailu suurelle merituulivoimapuistolle sopivasta paikasta käy kuumana Perämerellä – kahden hankkeen suunnitelmat julkaistiin muutaman viikon välein samalle alueelle. Retrieved 23.05.2024 from: https://yle.fi/a/74-20001611

[32] P2X Solutions. (2023). Ensimmäiset elektrolyysilaitteet saapuivat P2X Solutionsin Harjavallan vetylaitoksen työmaalle. Retrieved 23.05.2024 from: https://p2x.fi/ensimmaiset-elektrolyysilaitteet-saapuivat-p2x-solutionsin-harjavallan-vetylaitoksen-tyomaalle/

[33] Nordic Ren-Gas. (2023). Pori Energia ja Nordic Ren-Gas hankekehitysyhteistyöhön – hiilidioksidin talteenotolla ja jatkojalostuksella kohti hiilinegatiivista tulevaisuutta. Retrieved 23.05.2024 from: https://ren-gas.com/ajankohtaista/pori-energia-ja-nordic-ren-gas-hankekehitysyhteistyohon-hiilidioksidin-talteenotolla-ja-jatkojalostuksella-kohti-hiilinegatiivista-tulevaisuutta/

[34] Business Finland. (2024). Green North Energy monistaa Business Finlandin rahoittamaa vetylaitoskonseptiaan Poriin ja Kemiin – Tähtäimessä Suomen omavaraisuus ammoniakin tuotannossa. Retrieved 09.10.2024 from: https://www.businessfinland.fi/ajankohtaista/uutiset/tiedotteet/2024/green-north-energy-monistaa-business-finlandin-rahoittamaa-vetylaitoskonseptiaan-poriin-ja-kemiin--tahtaimessa-suomen-omavaraisuus-ammoniakin-tuotannossa

References

[35] Rauma. (2024). Selvitys vetytalouden mahdollisuuksista Raumalla. Retrieved 09.10.2024 from: https://www.rauma.fi/ajankohtaista/selvitys-vetytalouden-mahdollisuuksista-raumalla/

[36] Michaux, S. P., Vadén, T., Korhonen, J. M., & Eronen, J. T. (2022). Assessment of the scope of tasks to completely phase out fossil fuels in Finland. (p. 43). Retrieved 23.05.2024 from: https://tupa.gtk.fi/raportti/arkisto/18_2022.pdf

[37] Energiateollisuus. (n.d.). Sähköntuotanto. Retrieved 23.05.2024 from: https://energia.fi/energiatietoa/energiantuotanto/sahkontuotanto/

[38] Industrial Metallurgists. (n.d.). Hydrogen Embrittlement of Steel. Retrieved 23.05.2024 from: https://www.imetllc.com/hydrogen-embrittlement-steel/

[39] DNV. (2022). Hydrogen forecast to 2050. (p. 56). Retrieved 23.05.2024 from: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/

[40] Vanhanen, J., Pulkkinen, A., Salmi, W., Beniard, M., Järvinen, K., & Lehtomäki, J. (2022). Meriliikenteen vaihtoehtoisten polttoaineiden markkinoiden kehitys ja vaikutukset Suomeen suuntautuvan meriliikenteen kustannuksiin. (p. 33). Retrieved 23.05.2024 from: https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/164405/LVM_2022_13.pdf?sequence=1&isAllowed=y

[41] DNV. (2022). Hydrogen forecast to 2050. (p. 56-57). Retrieved 23.05.2024 from: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/

[42] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (p. 110). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[43] DNV. (2022). Hydrogen forecast to 2050. (pp. 56-57). Retrieved 23.05.2024 from: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/

[44] DNV. (2022). Hydrogen forecast to 2050. (p. 57). Retrieved 23.05.2024 from: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/

[45] Motiva. (2024). Vety. Retrieved 23.05.2024 from: https://www.motiva.fi/ratkaisut/kestava_liikenne_ja_liikkuminen/valitse_auto_viisaasti/energialahteet/vety

[46] Ocko, I. O., & Hamburg, S. P. (2022). Climate consequences of hydrogen emissions. Retrieved 23.05.2024 from: https://acp.copernicus.org/articles/22/9349/2022/

[47] Laursen, R., Patel, H., Dowling, M., Sofiadi, D., Ji, C., Nelissen, D., Király, J., van der Veen, R., & Pang, E. (2023). Potential of hydrogen as fuel for shipping. (p. 2). Retrieved 23.05.2024 from: https://www.emsa.europa.eu/publications/item/5062-potential-of-hydrogen-as-fuel-for-shipping.html

References

[48] European Clean Hydrogen Alliance. (2023). Learnbook: Hydrogen imports to the EU market. (p. 15). Retrieved 23.05.2024 from: https://www.entsog.eu/sites/default/files/2023-12/European%20Clean%20Hydrogen%20Alliance%20TD%20RT_Learnbook%20Hydrogen%20Imports%20to%20EU%20market_20231219.pdf

[49] Hyundai. (2020). Hyundai XCIENT Fuel Cell Heads to Europe for Commercial Use. Retrieved 23.05.2024 from: https://www.hyundai.news/eu/articles/press-releases/hyundai-xcient-fuel-cell-heads-to-europe-for-commercial-use.html

[50] Popular science. (2023). The world's first hydrogen-powered train has made its final stop. Retrieved 23.05.2024 from: https://www.popsci.com/technology/hydrogen-train-germany/

[51] Baird Maritime. (2023). VESSEL REVIEW | Sea Change – Hydrogen-fuelled demonstrator ferry for San Francisco Bay Area. Retrieved 23.05.2024 from: https://www.bairdmaritime.com/passenger/ferry/vessel-review-sea-change-hydrogen-fuelled-demonstrator-ferry-for-san-francisco-bay-area/

[52] Holtze, B. (2023). World's first liquid-powered hydrogen ship, MF Hydra, is powered by Ballard's fuel cells. Retrieved 23.05.2024 from: https://blog.ballard.com/marine/worlds-first-liquid-powered-hydrogen-ship-mf-hydra-is-powered-by-ballards-fuel-cells

[53] Baird Maritime. (2023). VESSEL REFIT | H2 Barge 1 – Dutch operator adds hydrogen-powered boxship to inland fleet. Retrieved 23.05.2024 from: https://www.bairdmaritime.com/shipping/boxships/vessel-refit-h2-barge-1-dutch-operator-adds-hydrogen-powered-boxship-to-inland-fleet/

[54] Helander, B. (2021). Merten mirai – maailman ensimmäinen vetykäyttöinen matkustaja-autolautta tähtää liikenteeseen 2027. Retrieved 23.05.2024 from: https://moottori.fi/uutinen/merten-mirai-maailman-ensimmainen-vetykayttoinen-matkustaja-autolautta-tahtaa-liikenteeseen-2027/

[55] MAN Truck & Bus. (2023). MAN Engines presents groundbreaking hydrogen combustion engine for off-road applications. Retrieved 23.05.2024 from: https://press.mantruckandbus.com/corporate/man-engines-presents-groundbreaking-hydrogen-combustion-engine-for-off-road-applications/

[56] Habibic, A. (2024). MAN ES and Mitsui E&S perform world's first hydrogen combustion test on marine 2-stroke engine. Retrieved 23.05.2024 from: https://www.offshore-energy.biz/man-es-and-mitsui-es-perform-worlds-first-hydrogen-combustion-test-on-marine-2-stroke-engine/

[57] Krol, A. (2023). Why do we blame climate change on carbon dioxide, when water vapor is a much more common greenhouse gas? Retrieved 23.05.2024 from: https://climate.mit.edu/ask-mit/why-do-we-blame-climate-change-carbon-dioxide-when-water-vapor-much-more-common-greenhouse

References

[58] Bertagni, M. B., Pacala, S. W., Paulot, F., & Porporato, A. (2022). Risk of the hydrogen economy for atmospheric methane. Retrieved 23.05.2024 from: https://www.nature.com/articles/s41467-022-35419-7

[59] Nebergall, J. (2022). Hydrogen internal combustion engines and hydrogen fuel cells. Retrieved 23.05.2024 from: https://www.cummins.com/news/2022/01/27/hydrogen-internal-combustion-engines-and-hydrogen-fuel-cells

[60] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2023). Managing Emissions fromAmmonia-Fueled Vessels. (p. 16). Retrieved 23.05.2024 from: https://cms.zerocarbon-shipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf

[61] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2023). Managing Emissions from Ammonia-Fueled Vessels. (p. 16). Retrieved 23.05.2024 from: https://cms.zerocarbon-shipping.com/media/uploads/documents/Ammonia-emissions-reduction-position-paper_v4.pdf

[62] Tae, C. (2021). Hydrogen Safety: Let’s Clear the Air. Retrieved 23.05.2024 from: https://www.nrdc.org/bio/christian-tae/hydrogen-safety-lets-clear-air

References for graphs, figures and tables

p.2 Figure 1:
DNV. (2023). Energy transition outlook 2023: Maritime forecast to 2050. (p. 24). Retrieved 23.05.2024 from: https://www.dnv.com/maritime/publications/maritime-forecast-2023/download-the-report/

pp.3-4 Figure 2:
Ringsgwandi, L. M., Schaffert, J., Brücken, N., Albus, R, & Görner, K. (2022). Current Legislative Framework for Green Hydrogen Production by Electrolysis Plants in Germany. (p. 3). Retrieved 23.05.2024 from: https://www.researchgate.net/publication/358926929_Current_Legislative_Framework_for_Green_Hydrogen_Production_by_Electrolysis_Plants_in_Germany

p.6 Table:
Solakivi, T., Paimander, A., & Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. (p. 2). Retrieved 23.05.2024 from: https://www.utupub.fi/bitstream/handle/10024/173681/1-s2.0-S1361920922003261-main.pdf?sequence=1

Bertagna, S., Kouznetsov, I., Braidotti, L., Marino, A., & Bucci, V. (2023). A Rational Approach to the Ecological Transition in the Cruise Market: Technologies and Design Compromises for the Fuel Switch. (p. 4). Retrieved 23.05.2024 from: https://www.researchgate.net/publication/366818830_A_Rational_Approach_to_the_Ecological_Transition_in_the_Cruise_Market_Technologies_and_Design_Compromises_for_the_Fuel_Switch

Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. Retrieved 23.05.2024 from: https://www.sciencedirect.com/science/article/pii/S0959652621008714?via%3Dihub

Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., & Liu, H. (2021). Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. Retrieved 23.05.2024 from: https://www.sciencedirect.com/science/article/pii/S0959652621030675?via%3Dihub

The Engineering ToolBox. (n.d.). Fuels - Higher and Lower Calorific Values. Retrieved 23.05.2024 from: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

European Commission. (2021). Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC. (Annex II). Retrieved 23.05.2024 from: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52021PC0562

References for graphs, figures and tables

p.6 Table:
Hürpekli, M., & Özsezen, A. N. (2023). Determination of combustion and emission characteristics of liquid Fischer-Tropsch diesel fuel synthesized from coal in a diesel engine. Retrieved 23.05.2024 from: https://www.sciencedirect.com/science/article/pii/S0196890423006970

Nair, A. (2016). Alternative Fuels for Shipping: Potential for reductions in CO2 emissions, Financial viability for ship owners and, Optimised fleet mix design for policymakers. (p. 26). Retrieved 05.06.2024 from: https://www.google.com/url?sa=t&source=web&rct=-j&opi=89978449&url=https://thesis.eur.nl/pub/41180/A.-Nair-Thesis-Final-441409-A.Nair.pdf&ved=2ahUKEwigvu_mga6HAxWBFBAIHcUxDfcQFnoECBYQAQ&usg=AOvVaw-2gONDv_4o4A7a8ZhjFtsD-

Sources of images

p.1 Adobe Stock: Federico Aliaksandr Siamko. (n.d.). Retrieved 30.08.2024 from: https://stock.adobe.com/images/container-cargo-ship-in-the-ocean-at-sunset-blue-sky-background-with-copy-space-nautical-vessel-and-sea-freight-shipping-international-global-business-logistics-transportation-import-export-concept/756026306

p.2 Adobe Stock: Yellow Boat. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/aerial-top-view-of-cargo-ship-carrying-container-and-running-for-export-goods-from-cargo-yard-port-to-custom-ocean-concept-technology-transportation-customs-clearance/483855922

p.3 Adobe Stock: PNG Lover. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/oil-refinery-plant-isolated-on-transparent-background/763105869?asset_id=763105869

p.4 Adobe Stock: PNG Lover. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/oil-refinery-plant-isolated-on-transparent-background/763105869?asset_id=763105869

p.5 Adobe Stock: PNG Lover. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/oil-refinery-plant-isolated-on-transparent-background/763105869?asset_id=763105869

Adobe Stock: malp. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/a-hydrogen-pipeline-to-houses-illustrating-the-transformation-of-the-energy-sector-towards-clean-carbon-neutral-safe-and-independent-energy-sources-to-replace-natural-gas-in-homes/498531471

p.6 Adobe Stock: bsd studio. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/preventing-workplace-injury-concept-icons-set-occupational-health-and-safety-idea-thin-line-color-illustrations-isolated-symbols-editable-stroke-roboto-medium-myriad-pro-bold-fonts-used/551487228?asset_id=551487228

p.7 Adobe Stock: Icon-Duck. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/lean-manufacturing-banner-vector-illustration-with-the-icons-of-six-sigma-management-quality-standard-industry-continuous-improvements-reduce-waste-improve-productivity-efficiency-keizen/672171945?asset_id=672171945

pp.8-9 Adobe Stock: Gondex. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/continuous-line-drawing-of-machine-gears-the-concept-of-gears-on-a-single-line-style-machine-machine-gear-technology-concept-in-single-line-doodle-style/566081642?asset_id=566081642

p.9 Adobe Stock: Gondex. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/continuous-line-drawing-of-machine-gears-the-concept-of-gears-on-a-single-line-style-machine-machine-gear-technology-concept-in-single-line-doodle-style/566081642?asset_id=566081642

p.10 Adobe Stock: The Deep Designer. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/638437077?asset_id=638437077

Sources of images

pp.2-21 Adobe Stock: Steves Artworks. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/blue-watercolor-sea-wave-texture-design-on-transparent-background/773410060?asset_id=773410060