Green Fuels (Green Hydrogen, Green LNG) in Maritime-Shipping for Centralized or Decentralized Heating, Electric Power Supply and Ship Propulsion

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Nowadays heavy fuel oil and Diesel are mostly used on merchant and passenger ships. Soon international and especially national governmental regulations will increase recommendations for maritime shipping in Europe and worldwide. The main reasons are high air polluting emissions like fine dust, Nitrogen Oxide and Sulphur Oxide, as well as the recommendations of reducing the Greenhouse Gas Emissions like Carbon Dioxide. Green fuels allow to reduce those emissions. Therefore, the International Maritime Organization (IMO) create the Maritime Pollution contract (MARPOL). The MARPOL Annex VI gives the possibility to define strictly controlled air polluting areas for SOx and NOx (Emission-Controlled Areas, ECAs or SECAs). The state-of-the-art shows that hydrogen and LNG can be safely operated and used to supply electric generating systems and drive systems. Especially cruise ships nowadays were constructed with LNG main propulsion engines. Conventional hydrogen or LNG are not CO_2 free. With green hydrogen or ammonia and green LNG, based on renewable electrical energy, CO_2 emissions could be reduced. The paper compares different green fuels to classical fuels in maritime applications, regarding pros and cons, emissions, safety aspects and the green renewable production of such fuels.

Round about 2.5 % (940 million tonnes of CO_2 per year) of worlds CO_2 emissions are emitted by maritime transportation sector [1]. That is more than the total CO_2 emissions of Germany (739 million tonnes in 2020) [2]. To stabilize and reduce the growth of global temperature, the national and international measures lead to limitations of using conventional fuels.

Based on the targets of International Maritime Organization (IMO) – Green House Gas Strategy, CO_2 emissions should be reduced at least 50 % until 2050 compared to 2008 and further to 0 % as soon as possible [3]. In November 2021, the International Chamber of Shipping (ICS) applied to IMO to be climate neutral until 2050. Additionally, the world-wide limitations of Sulphur Dioxide emissions of ships outside the emission control areas (ECAs) were reduced from 3.5% to 0,5 % since January 2020 [4].

Besides CO_2 emissions other air polluting gas emissions like Nitrogen Oxide (NOX), Sulphur Oxide (SOx), fine dust (PM and soot) must be reduced. Many regulations like TIER I and TIER II exists for ships calling a port on international seas and to use inland seaways. The SOx limit, for the SECA area (SOx Emission Control Areas) in the North Sea, Baltic Sea, north American coast, and US Caribbean, since 2015 is 0,1 %. NOx must be reduced by a limit of 80 % compared to TIER I directive for the NECA (NOx Emission Control Areas). The NECA include the North Sea, Baltic Sea, North American coast, and US Caribbean.

Therefore, the cruise tourism industry comes into public focus regarding air polluting emissions. The cruise industry can work on a green image through emission-reduced technologies and environment friendly green fuels.

Einsatz grüner Kraftstoffe (grüner Wasserstoff, grünes LNG) in der Schifffahrt zur zentralen oder dezentralen Anwendung zur Wärme- und Stromversorgung sowie zur Nutzung für den Hauptschiffsantrieb

Heutzutage werden hauptsächlich Schweröl und Diesel als konventionelle Kraftstoffe auf Fahrgastschiffen verwendet. Strenge internationale und insbesondere nationale regulatorische Rahmenbedingungen schränken zukünftig das Anlaufen eines Hafens mit konventionellen Kraftstoffen wesentlich ein. Hauptgründe dafür sind die hohen Emissionen solcher Kraftstoffe wie Kohlendioxid, Stickoxid, Schwefeloxid und Feinstaub. Grüne Gase (z. B. Wasserstoff) und grüne Kraftstoffe (z. B. grünes Methanol) ermöglichen die Reduzierung dieser Emissionen. Wasserstoff kann für einen sicheren Betrieb zur Versorgung von Stromerzeugungs- und Antriebssystemen eingesetzt werden. Konventioneller Wasserstoff oder konventionelles LNG sind nicht CO_2-frei. Mit grünem Wasserstoff, grünem Methanol, grünem Ammoniak und grünem LNG, basierend auf erneuerbarer elektrischer Energie, können die CO_2-Emissionen deutlich reduziert werden. In diesem Beitrag werden verschiedene grüne Kraftstoffe mit klassischen Kraftstoffen in maritimen Anwendungen (hauptsächlich Fahrgastschiffbereich) in Bezug auf Vor- und Nachteile, Emissionen und Sicherheitsaspekte verglichen.

Schlüsselwörter:

Grüne Kraftstoffe, Grüner Wasserstoff, Grünes LNG, Energieversorgung, Schiffantrieb, Treibhausgasemissionen, Kreuzfahrt, Fahrgastschiff

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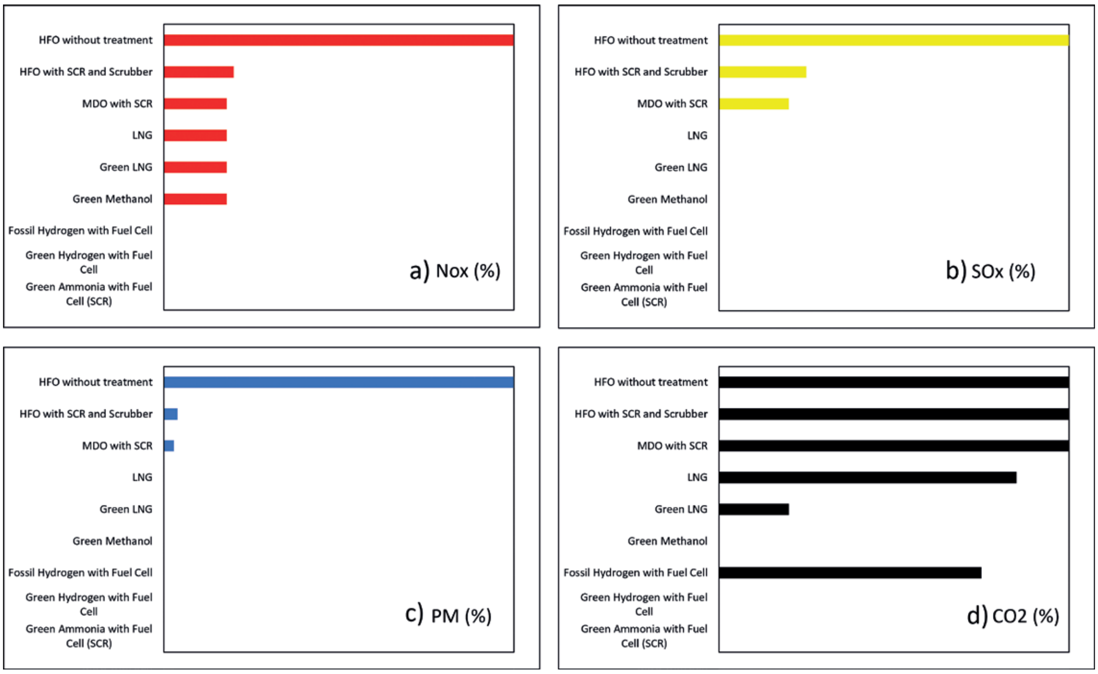


Figure 1: Air polluting gas emission a) Nitrogen Oxide (NOx), b) Sulphur Oxide (Sox), c) fine dust (PM), d) Carbon Dioxide (CO_2) for various fuel types and clean technology. Legend: HFO = Heavy Fuel Oil, MDO = Marine Diesel Oil, LNG = Liquefied Natural Gas, SCR = Selective Catalytic Reduction. Data source [5].

In the first step, the combination of fuel types and treating technologies generates a great effect to reduce those emissions. Equally the used energy in the production chain of ship fuels has a large impact on emission (from well to wheel). In the following, the paper compares fuel types, production chains and cleaning technologies particularly regarding air polluting gas emissions. Also, in the future fuel prices for conventional ships fuels could highly increase depending on the price of CO_2 emissions and limitations in oil production.

State of the Art Technologies to Reduce Air Polluting Gas Emissions

The air polluting gas emissions like Nitrogen Oxide (NOX), Sulphur Oxide (SOx), fine dust (PM and soot) could be reduced by using two different technologies. Scrubber technology ensures reduction of fine dust, particulate matter and especially Sulphur Dioxide. SCR Technology (Selective Catalytic Reduction) reduces the Nitrogen Oxide emissions.

In Figure 1 air polluting gases are represented in dependency of the used treating technology and the different fuel types. For the reference scenario of "100 %" a ship uses HFO as fuel without any cleaning technology.

The amount of emission reduction depends on the production chain, e. g., conventional LNG vs. green LNG. Ammonia is defined as a green fuel like hydrogen, if the production chain based on green electrical energy. Additionally, ammonia can be set as a green fuel when ammonia will be delivered as byproduct from industrial processes.

The NOx emissions in Figure 1a for HFO or Marine Diesel Oil (MDO) as fuels combined with treating technologies illustrate no difference compared to conventional LNG. Also, green LNG and green methanol reduce NOx emissions not really. Only green hydrogen reduces NOx emissions to zero.

The Sulphur Oxide emissions (Figure 1b) can be reduced at least to 20 % using conventional fuels with Scrubber technology. With green fuels, SOx emissions can be significantly reduced.

In Figure 1c, the particulate matter (PM) can be nearly eliminated by utilising the Scrubber as cleaning technology using the fossil fuels MDO or HFO. For particulate matter the advantages of applying green fuels are very low, and it reduces only the last 3 % of PM.

Appling treating technology (Scrubber and SCR) combined with conventional fuels have no Carbon Dioxide (CO_2) reduction effect (Figure 1d). Conventional hydrogen, based on fossil coal and natural gas, reaches a CO_2 reduction potential less than 25 %. Green methanol, green ammonia and green hydrogen enable to reduce CO_2 to a minimum. The fuel production chain (well to wheel) essentially influences the CO_2 emissions respectively CO_2 reduction. In addition, it is important to mention if using LNG or other methane fuels in combustion engines, there could be a methane slip. The methane slip can be up to 2% in e.g. duel fuel engines. The impact of methane on global warming is 25 times higher than Carbon Dioxide. Methane slip can be eliminated by a high temperature or catalytic treatment of the exhaust.

General outcome by comparing fuel types: to get a green and clean cruise and in general maritime sector, green fuels are needed.

Highly Efficient Technologies

By increasing the overall efficiency of e. g. the propulsion drive of a cruise ship , the specific energy consumption can be reduced. Figure 2 shows the specific ship engine power per weight (kW/Gt).

The cruise ship Radiance of the Seas represents the benchmarking baseline with 0.44 kW/Gt. Through the last 17 years the installed specific power was reduced by -55% to 0.20 kW/Gt on the ship AiDAnova. Also, the time steps to increase efficiency rapidly decrease from 7 years to 4 years.

Physical laws and technologies limit the increase of efficiency. On modern passenger ships also, energy saving electric components with less energy consumption are installed. There is not a real potential to decrease energy consumption by reinstalling new equipment.

On the one hand, if energy efficiency increases the specific amount of energy decreases. On the other hand, because of bigger ship sizes and number of ships worldwide, the total energy consumption in cruise sector increases. It´s called Rebound Effect. Therefore, it cannot be expected to further increase of efficiency or reduce energy consumption. Just applying new technologies can optimize the overall emissions of ships energy supply systems.

General outcome of energy efficiency technologies: with energy efficiency technologies we reduce CO_2 emissions, but we do not save them.

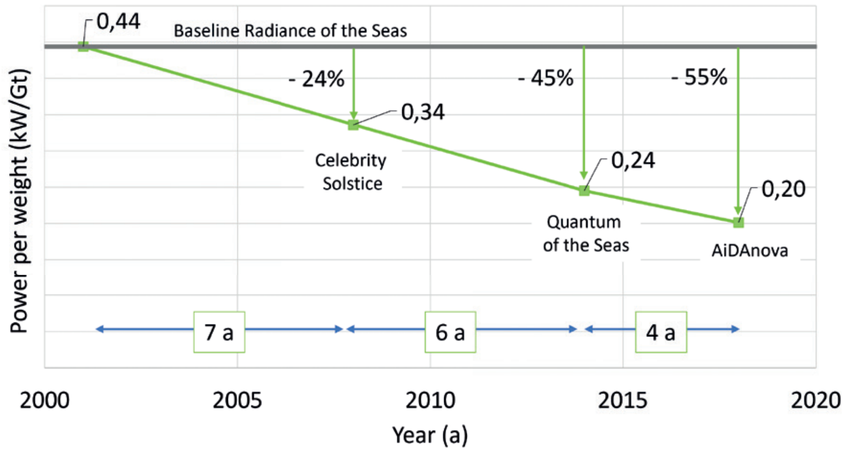


Figure 2: Specific ship engine power per weight (kW/Gt) and percentage of reduction potential over the last years for selected cruise ships. Data source [5].

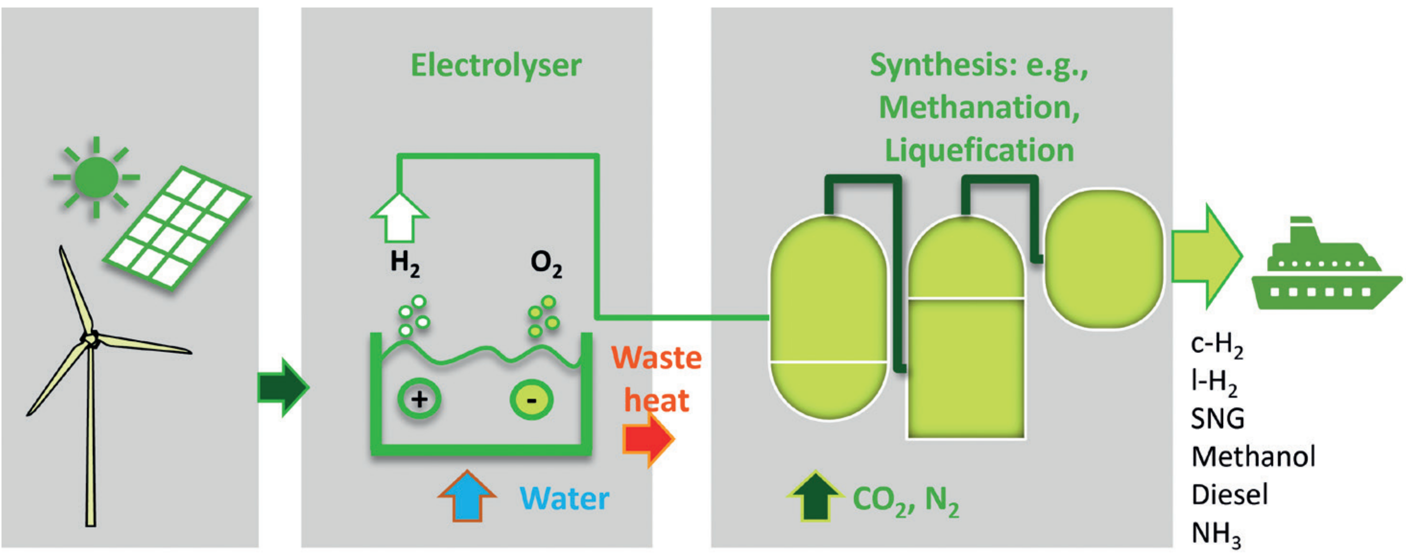
Green Fuel Production Chain

Electrical energy could be a support to mobility or transport sector by power lines, batteries hybrid systems or green fuels. For the maritime sector only, hybrid systems (system combination e. g., green fuels and batteries) or green fuels are practicable, because of the weight and distances.

Figure 3 shows the green fuel production chain. Due to conversions steps, for example form electrical energy to hydrogen, energy will be lost (30-40%). Renewable electrical energy (wind or photovoltaic) is transferred to other energy forms like green hydrogen, green SNG (Synthetic Natural Gas), green LNG (Liquefied Natural Gas) or green methanol. Green Ammonia (NH3) could be also used as a future green fuel for maritime sector.

Green hydrogen could be delivered to consumers like ships. Otherwise, green hydrogen could be transformed with CO_2 through different synthesis steps to green fuels like methanol or

Figure 3: Green fuel production chain based on renewable electrical energies e. g. wind, which feed-in an electrolyser followed by different synthesis steps to produce e. g. methanol [6].



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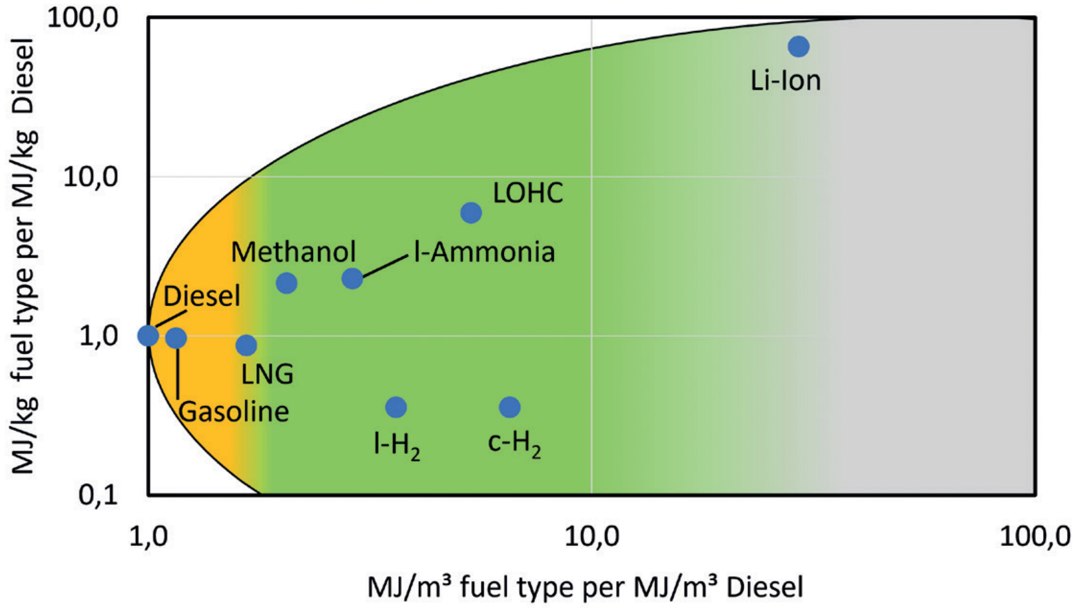

Figure 4: Standardized energy densities (gravimetric: MJ/kg and volumetric: MJ/m³) of different fuel types, based on Diesel.

SNG. Green SNG is the basis for green LNG. Green CO_2 could be taken from biogas plants or in the future captured from air.

Storage Problems Using Green Fuels

Also bunkering green fuels is a future task. The energy density (gravimetric and volumetric) of liquid or gaseous fuels plays an important role.

In Figure 4, standardized energy densities (gravimetric: MJ/kg and volumetric: MJ/m³) of different fuel types, based on Diesel, are shown. High energy density is reached with Diesel. Those energy densities are needed for long distances and big propulsion drive systems with a high energy consumption.

On ships, the space limits the fuel storing. For example, atmospheric hydrogen tanks need seven times more space than HFO or MDO tanks. But after all, hydrogen, batteries and methanol fuels are not a real alternative for international ship transportation. Green LNG and ammonia show comparable advantage in terms of storage space on long distance seaways and in future could have a high availability at bunkering terminals.

Also bunkering for future fuels must be solved. HFO, Diesel and most times conventional LNG are available at international ports in Europe and abroad. Green methanol and hydrogen could be taken for near coast or river shipping. But also, combining fuel types can make sense: for example, Diesel or (green) LNG for the main ship propulsion drive system and green methanol or green hydrogen for central or decentralised electric energy production to substitute the conventional Diesel-electric generating systems (auxiliary Diesel). This can improve the overall CO_2 footprint and reduces all noxious gas emissions.

Explanation of Figure 4: Orange area: fuel types similar (weight and volume) to Diesel. Green area: fuel types probably useable in costal and river shipping. Grey area: fuel types are not meaningful in shipping sector. For example: Li-Ion batteries need 30 times more space and the weight are 66 times higher compared to Diesel. Data Source [5]. Legend: l-H2 = Liquefied Hydrogen c-H2 = Compressed Hydrogen, l-ammonia = Liquid Ammonia, LOHC = Liquid Organic Hydrogen Carrier, LNG = Liquefied Natural Gas, Li-ion = Lithium-Ion Battery.

Fuels Cells and Hydrogen Applications on Ships

With fuel cells or combustion engines hydrogen can be transferred to electricity and heat. Highest efficiencies are reached with fuel cell. At first the kind of operation must be defined before choosing fuel cell operation. Requirements could be a fast start up response on electrical energy demand (cold start up and handle transient loads) and a high efficiency at partial load. In addition, the cell should operate on low temperatures (because of fire protection and safety aspects) and should be easy to maintain.

The fuel cell technology can be basically divided into two different principles. The one principle is based on a solid oxide fuel cell type which needs very high temperatures during operation (SOFC – Solid Oxide Fuel Cell). The second type is based on a proton exchange membrane (PEMFC - Proton Exchange Membrane Fuel Cell).

The proton exchange membrane fuel cell is available in a low (LT) and high temperature (HT) configuration. The LT-PEMFC cell starts-up in less than 10 seconds. The reaction time on transient loads is less than 5 seconds. The operation temperature compared to the other types is low. Only the lifetime can be lower than at the other fuel cell types and the required fuel purity is higher compared to the other systems.

The utilization of hydrogen on ships is also based on storage types (decentralised or central power systems). The main applications on ships are heating, warm water production and electrical energy production. The fuel combines this effort.

On the one hand, a centralized fuel cell system in the ship main machine area for heat and electricity production can be installed. So, the existing infrastructure like hot water pipes and the electrical grid can be used to deliver the energy to passenger compartments. On the other hand, the fuel cell can be placed decentralized in different ship sections. In this case it is not necessary to install water pipes and cables through all fire protection areas on ship. The main disadvantage in this scenario: each fuel cell needs its own tank system (a lot of installation effort), but that increases the system reliability additionally.

Conclusion

Solutions to reduce global warming must be established. We can´t go on as we did in the last 150 years. The transport sector like shipping is responsible for 2.5 % of CO_2 emissions. To reduce CO_2 emission different fuel types solutions are on the future market.

CO_2 emissions could be reduced with green fuels (green hydrogen, green ammonia) until 0 %. The type of green fuel depends on specific parameters like specific volumetric and gravimetric density. Also, future fuel prices could highly increase because of the limiting in their nature, and in pricing of CO_2 emissions.

Green LNG should be used for main engine drives on long seaways. LNG offers highest energy densities of green fuels. The LNG availability rises due to expanding LNG-terminals in seaports. Refuelling time is important for HD-Trucks. Using LNG leads to the same refuelling times as Diesel (up to 150 l/min). LNG Boil-Off is no issue for engines with high power density. Well-to-Tank economy depends on the length of transport route and production. A lot of new ships constructed are nowadays built with an LNG driving system. With green LNG conventional LNG could be 100 % substituted. Green LNG must be produced with climate neutral green CO_2. Otherwise, there will also be climate-damaging CO_2 emissions.

Methanol would be used for coastal and river shipping. Methanol is toxic but it is easy to handle.

With green hydrogen and green ammonia, CO_2 could be reduced to 0 %. Green hydrogen can be used for heating and electrical energy production. The fuel supply chain should include fuel production only by green energy from wind or solar to reach acceptable emission reductions. Early switching to green fuels is decided upon popularity on customer markets. Technical solutions for implementation on ships are available on markets. Nice energy densities, to store hydrogen, can be reached with high pressure systems. LOHC as storage media is maybe a future solution to store hydrogen.

Because of their weight and volume, batteries are not the best solution for the shipping sector.

Other air polluting emissions like Nitrogen Oxide (NOx), Sulphur Oxide (SOx), fine dust (PM and soot) must be reduced. Regulations and prohibition of using seaways and harbours like the TIER directive or NECA and SECA areas lead the ship owners to change something.

With highly efficient engines the specific energy amount in kW/tonnes could be reduced.

With green fuels a new image, the green image for cruise tourism industry can be established. Surveys have shown that tourists are able and willed to support green solutions e. g. green fuels for cruise ships.

Keywords:
green fuels, green hydrogen, green LNG, power supply, ship propulsion, greenhouse gas emissions, cruise tourism

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